Federal Reserve Bank of San Francisco
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To: Our Readers

From: Robert T. Parry
President
and Chief Executive Officer

John P. Judd
Senior Vice President
and Director of Research

Since 2000, the *FRBSF Economic Review* has featured policy-related articles and a compendium of the Economic Research Department's research publications and activities during the preceding year. This issue includes a special focus on the work of the Department's new Center for the Study of Innovation and Productivity (CSIP). Two of the featured articles provide a broad overview and analysis of the recent information technology investment boom and bust, from both a national and a regional perspective. The third article, based on the keynote address at the November 2003 CSIP conference, provides a perspective on assessing the contributions of information technology and other sources of innovation to the acceleration in productivity growth since the mid-1990s. Following the articles is a brief description of the Center's activities in 2003 and its plans for 2004, written by CSIP's Executive Director, Fred Furlong, Vice President, Financial and Regional Research, and its Director, Mary Daly, Research Advisor.

This new Center joins the Department's Center for Pacific Basin Monetary and Economic Studies as a locus of specialized economics expertise within the Federal Reserve System. CSIP supports a broad array of research in recognition of the diversity of the sources of innovation and the prevalence of the innovation–productivity link across sectors and through time. The scope includes macroeconomic and microeconomic research on innovation and productivity and their links to global, national, and regional economic performance and to firm and labor market behavior.

CSIP grew out of several years of effort on the part of the Economic Research Department to build expertise in the areas of innovation, technology, and productivity, topics of critical importance to the national economy and monetary policy, as well as to the Twelfth Federal Reserve District, given its prominent technology centers.

CSIP affiliates include FRBSF staff economists and visiting scholars. Their basic research appears in the Department's Working Papers series. The Center's activities include conferences and a Joint Seminar Series with the University of California at Berkeley and Stanford University. CSIP's website (www.frbsf.org/csip) contains links to these publications as well as data and other features for both researchers and nonspecialists. The first issue of "CSIP Notes," a special series of the *FRBSF Economic Letter*, summarizes the research presented at the inaugural conference.

We are pleased to focus much of this issue of the *FRBSF Economic Review* on our new Center, whose work will not only enhance the analysis of Federal Reserve policy issues but also be a valuable resource to other researchers and to the public.

The Federal Reserve Bank of San Francisco's *Economic Review* is published annually by the Research Department under the supervision of John Judd, Senior Vice President and Director of Research, and Fred Furlong, Vice President, Financial and Regional Research, and Executive Director, Center for the Study of Innovation and Productivity; Reuven Glick, Vice President, International Research, and Director, Center for Pacific Basin Monetary and Economic Research, and Glenn Rudebusch, Vice President, Macroeconomic Research. The publication is edited, compiled, and produced by Anita Todd, Research Editor.

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Performance of Urban Information Technology Centers: The Boom, the Bust, and the Future*

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After being emblematic of the U.S. economic surge in the late 1990s, urban areas that specialize in information technology (IT) products have more recently been struggling with the aftermath of the IT spending bust. To what degree can they bounce back and reemerge as leaders of innovative activity and production in the IT sector? We examine the characteristics of some of the nation's leading IT centers, linking these characteristics to a discussion of economic research concerning the sources of growth in urban industrial centers. Although each of these IT centers was hit hard by the IT bust beginning in 2000, the full impact varies depending on the size, density, and composition of the local IT sector. Some IT centers are better positioned than others to resume a rapid growth path as the IT sector recovers, depending on factors such as reliance on manufacturing versus services, diversity of the product base, innovative capacity, and ability to respond to changing conditions such as the recent rise in IT imports and overseas production.

1. Introduction

Information technology (IT) producers were among the key drivers of the national economic expansion during the late 1990s and in 2000, helping to spur robust growth in output, productivity, and income. Between 1995 and 2000, IT-producing businesses accounted for nearly one-third of U.S. GDP growth and, by one estimate, nearly two-thirds of the surge in productivity growth, despite accounting for less than 9 percent of total output at the start of the period.[1] At its peak, the IT sector was growing more than four times as quickly as the overall economy. This growth was driven largely by business investment in IT products, which increased rapidly throughout the period.

While the national IT boom helped spur growth throughout the U.S. economy, certain urban areas were especially well-positioned to take advantage of the IT spending surge. These urban IT centers were at the forefront of expansion in the U.S. IT sector, posting extraordinary gains in employment and income. As in the past, Silicon Valley (the San Francisco Bay Area more generally) was among the nation's leading IT centers. However, the 1990s also marked a time when several other urban IT centers, including Portland, Seattle, Washington, D.C., and Austin came of age. All of these centers were emblematic of the IT boom, posting substantial increases in IT output and serving as home bases to researchers and companies that played an integral role in bringing innovation to the marketplace.

Just as the IT boom disproportionately benefited many regional centers of IT production, the IT bust left them struggling to regain economic stability. Battered by the

*We thank Geoffrey MacDonald and Ashley Maurier for excellent research assistance, Mark Doms for some of the data used, Fred Furlong for helpful comments, and Anita Todd for editorial assistance.

1. Data on the contributions of IT to GDP come from the Bureau of Economic Analysis (BEA) GDP releases. See Stiroh (2002) for analysis of the IT sector's contribution to productivity growth. Although the surge in productivity growth from 1995 to 2000 was dominated by IT-producing sectors, increases in productivity more generally were broad-based, with most sectors realizing productivity gains over the period.

downturn in business investment in IT equipment and software, several IT centers experienced some of the most severe net job losses in the nation. This reversal of fortune has prompted some observers to question whether cities that were at the forefront of the IT boom can return to prominence as centers of innovative activity and production. Which cities can best respond to newly emerging growth patterns in the IT sector, and what characteristics play key roles in this process?

To address these questions, we focus on the rise and fall of a sample of urban IT centers during the IT "boom and bust" cycle from 1995 through 2003. We focus on a set of ten metropolitan areas that experienced rapid growth in their own IT sectors and made a substantial contribution to national IT growth. The key characteristics that helped these areas to grow—concentrations of IT employment and wages, high levels of research and development (R&D) and patent activity, and highly skilled labor forces—appear to have survived the bust. These factors bode well for the urban IT centers to remain focal points for IT innovation and production. That said, the future is not without challenges; changes in product demand, business investment patterns, and overseas production will put pressure on IT centers to evolve, with the likelihood that some will adapt better than others.

We begin in Section 2 by discussing economic evidence regarding the development and dynamics of specialized industry clusters in cities. We then describe our sample of urban IT centers in Section 3, and in Section 4 we examine the extent to which they exhibit economic characteristics that are consistent with IT specialization and sectoral growth. These sections provide the background for the next two sections, in which we analyze the boom and bust cycle and the responsiveness of the IT centers to key growth determinants: business investment spending and the rising role of overseas production. We conclude in Section 7 with a brief comparative overview of the growth prospects for our set of major urban IT centers.

2. Urban and Industry Growth

What determines the formation of urban IT clusters and their growth? Research on these specific questions in economics and related fields is quite limited.[2] However, a substantial amount of research has been conducted that investigates the general determinants and patterns of economic growth at the urban level, and this research is relevant to the issues we address in this paper.

On the formation of specialized industry clusters, the work of Ellison and Glaeser (1997, 1999) is especially instructive. They note that Silicon Valley-style concentrations of industries can arise through two broad features of urban economies. The first is the presence of location-specific cost advantages—i.e., differences in input costs due to climate and geography, access to raw materials, and available supplies of different categories of labor. Although most inputs into the IT production process—financial capital, specialized machinery, raw materials, etc.—are unlikely to exhibit substantial price variation across geographic areas, variation in the availability and relative price of skilled labor (such as college-educated workers) may represent one important source of cost variation for IT producers.

An additional mechanism for the development of specialized IT centers is the presence of beneficial knowledge spillovers among firms within the same industry and geographic area. To the extent that these "agglomeration economies" exist and contribute to local economic specialization, they create the potential for "increasing returns" in production, or increased productivity in the locally concentrated industry as output increases. The tendency for initial industry leaders, such as Silicon Valley, to maintain or expand their innovative and productive edge over time is consistent with increasing returns in local IT centers. Moreover, this process of increasing returns through knowledge spillovers is likely to function most effectively in markets with an abundant supply of highly skilled labor, which suggests a potentially positive interaction between location-specific cost advantages and knowledge spillovers in determining IT industry growth.

Saxenian (1994) has identified some of the key features of agglomeration economies in Silicon Valley's IT sector, including knowledge transmission through employee mobility (often entrepreneurial), supportive and activist financial institutions (see Hellman and Puri (2002) for evidence on the role of venture capitalists), and the presence of knowledge centers such as research universities and institutes (see Audretsch and Feldman (1996) regarding the importance of knowledge spillovers from these sources). More general evidence, which systematically models growth performance across cities, also supports the importance of knowledge spillovers in urban IT centers. Beardsell and Henderson (1999) find strong evidence of

2. The most well-known work is Saxenian's (1994) highly cited book comparing Silicon Valley with the Route 128 area near Boston. DeVol (1999) focuses on the contribution of the IT sector to growth in cities, while Cortright and Mayer (2001) emphasize the role of specialization for growth in urban high-tech centers. Drennan's (2002) definition of the "information" sector excludes manufacturing and includes a broad array of services not in our definition (for example, financial services, legal services, and other professional services); as such, his comprehensive analysis of the information sector and urban growth is not directly relevant to our work.

positive spillovers at the local level in an analysis restricted to the computer industry. Moreover, Audretsch and Feldman (1996) find that industries in which knowledge spillovers are more prevalent have the greatest propensity to exhibit innovative clusters at the local level.

Strictly speaking, Ellison and Glaeser's arguments regarding the sources of localized growth refer to the degree of geographic concentration of total U.S. output in a sector, hence the overall size (rather than density) of local IT sectors in our setting. However, the benefits of agglomeration economies are likely to be most pronounced when production is locally dense (constitutes a large share of output), since the benefits of knowledge spillovers may be diluted when the IT sector must compete more vigorously with other sectors for scarce knowledge resources. Thus, it is likely that specialization is important for IT sector growth, in the sense that an urban area must achieve a high density of IT activities as a share of overall economic activity in order to realize the benefits of agglomeration.[3]

Interestingly, other research finds that industrial diversity, rather than specialization, plays a key role in urban innovation and growth (Feldman and Audretsch 1999, Duranton and Puga 2001).[4] This is not necessarily inconsistent with the role of IT specialization, however, as it may also be true that diversity within the IT sector supports innovation. In particular, Duranton and Puga (2001) emphasize that innovative activities are most common and effective in diversified production environments, in which firms searching for the best products and processes benefit from a wide range of possibilities. The process of knowledge spillovers in the IT industry, achieved through employee mobility and related factors, functions as a critical delivery mechanism for realizing the benefits of diversified product environments. Duranton and Puga also note that it is common for firms to start up in diversified cities and then move to more specialized production locales; this is consistent with the tendency for IT firms to have headquarters in IT centers but to locate production facilities in lower-cost locations increasingly over time.[5] Moreover, by ensuring a wide range of production processes and of products, a diverse local IT sector may possess the advantage of enhanced flexibility in response to changing conditions in IT markets; these may include changes in patterns of demand, changing domestic and overseas cost conditions, and other broad changes that affect the demand and supply for IT products and services.

To summarize, it appears that urban areas that have a large IT sector and that have a relatively high density of IT activities may have two key advantages over other areas in regard to IT innovation and production. First, high IT density enables a region to capitalize on local increasing returns to IT innovation and production, thereby reducing costs and enhancing productivity within its IT sector. This is especially true when highly skilled labor is in abundant supply. In addition, having a large local IT sector increases the likelihood of diversity *within* the IT sector, since growth constraints related to market size are likely to be less binding when the product array is relatively broad. In addition to providing flexibility to respond to changing IT industry demand and cost conditions, diversity within the IT sector may provide an impetus for IT innovative activities by allowing firms to access a wide range of product and process options. As such, a combination of size and density in the IT sector may be optimal and go a long way towards explaining the continuity of an industry leader such as Silicon Valley.

3. IT Centers: Definition and Sample

Before defining our sample of urban IT centers, it is important to define what is meant by "IT." Our broad definition of the IT sector is intended to capture the manufacture and service-based provision of advanced information technologies that rely on programming or other automated control mechanisms.[6] On the manufacturing side, computers and communications equipment, and their primary building blocks—semiconductors and other advanced electronic machinery—form the core of this industry. IT manufacturing also includes the production of a variety of advanced measuring and testing equipment, such as photonics and electromedical and aeronautical devices, along with consumer electronics. The services side includes firms that provide wired and wireless communication technologies, along with deliverers of Internet and other computer programming, design, and management services and research and engineering services. We use this broad definition wherever possible, although for much of what we do below, data constraints require that a narrower definition be applied (we discuss deviations where appropriate).

3. Ciccone and Hall (1996) provide persuasive evidence that the density of overall economic activity in local economies, rather than their size, is a key determinant of economic growth.

4. The importance of industrial diversity for urban growth is an idea often traced back to Jacobs (1969).

5. For example, the growth of IT production and employment in Oregon and other relatively low-cost states over the past decade has occurred in part because existing companies such as Intel have relocated production facilities from high-cost areas such as Silicon Valley (while maintaining research and management facilities in their origin cities).

6. The broad definition that we use is generally identical to the definition used by the American Electronics Association (see AEA 2003). It includes North American Industrial Classification System (NAICS) industry codes 33400, 333200, 333300, 511200, 511700, 518000, 541500, 541700, and 611400 (see also footnote 9).

Notably excluded from this definition are the biotechnology and pharmaceuticals industries ("biotech"). These sectors share some of the key characteristics of our IT industries, most notably a knowledge-intensive production process, as reflected in an advanced skill base and extensive R&D outlays and patenting activity. However, these industries tend to play a much smaller role than IT industries in local economies, and the demand and innovation cycles in these industries are independent of those in IT; for example, the biotech and pharmaceutical industries did not share in the recent boom-and-bust cycle experienced by our more narrowly defined providers of IT goods and services. These features of biotech support its exclusion from an analysis of the shifting fortunes of IT centers.

With a definition of IT-producing industries in hand, we selected a sample of metropolitan areas where these industries play an important role. Our definition of IT centers relies on the concept of "metropolitan statistical areas" (MSAs), as defined by the U.S. Office of Management and Budget and as used by federal statistical agencies. In general, MSAs consist of a core area containing a substantial population nucleus, together with adjacent communities that have a high degree of socioeconomic integration with that core. To identify our IT centers, we applied the broadest available MSA definition, which in most cases corresponds to combined MSAs that form a "consolidated" MSA, or CMSA. Each of these areas is tied together internally by economic factors, such as commuting patterns and business ties, that form a shared economic base.[7]

We chose our exact set of cities by considering the importance of the IT sector in the local economy and the contribution of the local IT sector to total national IT activity. Starting with a sample of sixteen MSAs known to have large IT sectors or high IT shares of local activity (American Electronics Association 2000), we measured the importance of IT to the local economy by the share of IT industries in total nonfarm wage and salary payments (payrolls) in 2000 and payroll growth between 1995 and 2000. Similarly, we measured the contribution of local IT sectors to national IT activity by the share of local IT sectors in national IT payrolls.[8] Attaching equal weight to these factors, we then ranked cities based on the combined magnitude of these three factors.

The resulting list of ten urban IT centers (in alphabetical order) is Atlanta, Austin, Boston, Dallas, Denver, Los Angeles, Portland, the San Francisco Bay Area, Seattle, and Washington, D.C. Table 1 lists the principal IT product specializations of each. In general, these are large MSAs as measured by population. Except for the Los Angeles area and Portland, each boasts personal income per capita above the U.S. metro average, with the San Francisco Bay Area achieving a level that is about 50 percent above the U.S. metro average. (See the Appendix for a table listing population and per capita income for the ten IT centers in our sample.)

The factors contributing to our ranking are listed in Table 2 (from this point on, we use shortened names for the broad MSAs listed in Table 1). As in the nation as a whole, IT-producing industries made a disproportionate contribution to overall economic growth in our IT centers. This can be seen by comparing the IT share of payrolls in 1995 (Table 2, column 1) to the IT contribution to total payroll growth (column 3). For the ten IT centers on which we focus, the IT growth contribution is larger than the IT growth share (and indeed, except for Los Angeles, is larger than the IT growth contribution for the nation as a whole). The contribution of IT to overall payroll growth was especially large in the San Francisco Bay Area, accounting for over one-third of the total. The IT contribution to the growth in payrolls also was quite large in Portland, Seattle, and Washington, D.C., ranging from twice to more than two and a half times as large as the initial IT share. On average, the contributions of IT-producing sectors to payroll growth were about one and a half to two times as large as their share of total payrolls in 1995, with West Coast IT centers exhibiting especially large absolute contributions. The sole exception is Los Angeles, which exhibits an IT contribution to local growth somewhat below that for the U.S. as a whole. However, that MSA's inclusion in our

7. For example, as indicated later in this section, rather than focusing narrowly on "Silicon Valley," which corresponds roughly to the San Jose MSA in California, we include the San Francisco and Oakland MSAs in our definition of the San Francisco Bay Area IT center. Although the San Jose MSA traditionally exhibits the highest IT density of any MSA nationwide, San Francisco and Oakland also are relatively dense centers of IT activity, and the connections between IT and related firms throughout the region are strong (similar to the "Route 128" region in and around Boston).

8. Tabulations of IT sector shares of total nonagricultural employment and wage payments are the most readily available and commonly cited measures of IT production activity and shares. These data are from the U.S. Bureau of Labor Statistics' (BLS) Covered Employment and Wages (CEW) program (now called the Quarterly Census of Employment and Wages), which provides data on all establishments covered by state and federal unemployment insurance provisions. The available degree of industry detail therefore is quite large, enabling implementation of a relatively precise definition of the IT sector. Excluded establishments constitute a very small share of urban employment in general. Although it would be preferable to use output measures, to make these tabulations comparable to the national figures cited in the introduction, the requisite data on output by state and industry are not available.

TABLE 1
URBAN IT CENTERS AND PRINCIPAL PRODUCT SPECIALIZATIONS

Region	Product Specializations
Atlanta, GA (MSA)	Databases, Telecommunications
Austin-San Marcos, TX (MSA)	Semiconductors, Computers, SME
Boston-Worcester-Lawrence-Lowell-Brockton, MA-NH (NECMA)	Computers, Medical Devices, Software
Dallas-Fort Worth, TX (CMSA)	Communications Equipment, Semiconductors, Telecommunications
Denver-Boulder-Greeley, CO (CMSA)	Data Storage, Communications Equipment, Telecommunications, Software
Los Angeles-Riverside-Orange County, CA (CMSA)	Household Audio and Video Equipment, Search and Navigation Equipment
Portland-Salem, OR-WA (CMSA)	Semiconductors, Display Technology, SME, Wafers
San Francisco-Oakland-San Jose, CA (CMSA)	Semiconductors, Computers, Software, Communications Equipment, SME, Data Storage
Seattle-Tacoma-Bremerton, WA (CMSA)	Software
Washington-Baltimore, DC-MD-VA-WV (CMSA)	Databases, Internet Service, Telecommunications

Notes: SME refers to Semiconductor Manufacturing Equipment. MSAs are Metropolitan Statistical Areas; CMSAs are Consolidated Metropolitan Statistical Areas; and NECMA is New England County Metropolitan Area.
Sources: Center on Urban and Metropolitan Policy (The Brookings Institution) and authors' tabulations of U.S. BLS data.

TABLE 2
IT PAYROLL DEVELOPMENTS IN THE BOOM

Region	IT share of MSA total payrolls (%) 1995 (1)	IT share of MSA total payrolls (%) 2000 (2)	IT share of MSA total payroll growth (%) 1995–2000 (3)	Local IT share of U.S. IT payrolls (%) 2000 (4)
Sample MSAs				
Atlanta	10.1	13.4	16.3	2.5
Austin	15.8	16.9	21.2	1.1
Boston	12.2	12.6	16.2	4.4
Dallas	10.1	16.2	20.5	3.9
Denver	12.7	16.0	21.5	2.3
Los Angeles	7.9	9.4	12.2	5.0
Portland	9.4	14.3	23.5	1.4
S.F. Bay Area	21.4	30.0	37.2	15.1
Seattle	9.6	18.3	25.5	3.4
Washington, D.C.	10.5	12.2	21.0	5.0
Excluded MSAs				
Chicago	6.8	8.5	11.7	3.3
Minneapolis	10.6	10.8	14.5	1.8
New York	6.2	6.1	5.9	5.5
Raleigh	16.9	12.8	14.2	0.8
United States	7.5	8.9	14.8	—

Source: Authors' tabulations using data from the U.S. BLS.

sample is largely determined by its overall size and resulting large contribution to total national IT payrolls (column 4).

These numbers imply an additional interesting feature of the distribution of IT production activities. In particular, the relatively large contribution of IT payrolls to total payroll growth in these IT centers is consistent with increased concentration of national IT payrolls in these urban areas. Additional calculations (not shown) confirm that this is indeed the case: with the exceptions of Boston and Los Angeles, the share of national IT payrolls increased for our IT centers between 1995 and 2000. In 2000, our ten urban IT centers accounted for 44 percent of national IT payrolls.

For comparative purposes, Table 2 also lists figures for four MSAs not included in our primary sample (we also examined data for Rochester and Phoenix, which were ranked below all other cities in our list). The New York and Chicago metro areas both made a large contribution to total national IT payrolls (column 4), but the relatively small contribution of IT to overall activity in these areas led to their exclusion from our primary sample. The remaining two MSAs, Minneapolis and Raleigh, lacked in both these measures, neither making a large contribution to national IT payrolls nor seeing a large contribution by IT to local growth. Moreover, each of these excluded cities saw a decline in its share of national IT payrolls between 1995 and 2000.

4. Profiles of Urban IT Centers

We now examine the extent to which the urban IT centers in our sample conform to the characterizations of specialized urban industrial centers described in Section 2. We begin by considering the intensity of IT production and innovative activity and the availability of skilled labor in each of these centers. We then describe the level of diversification within IT centers.

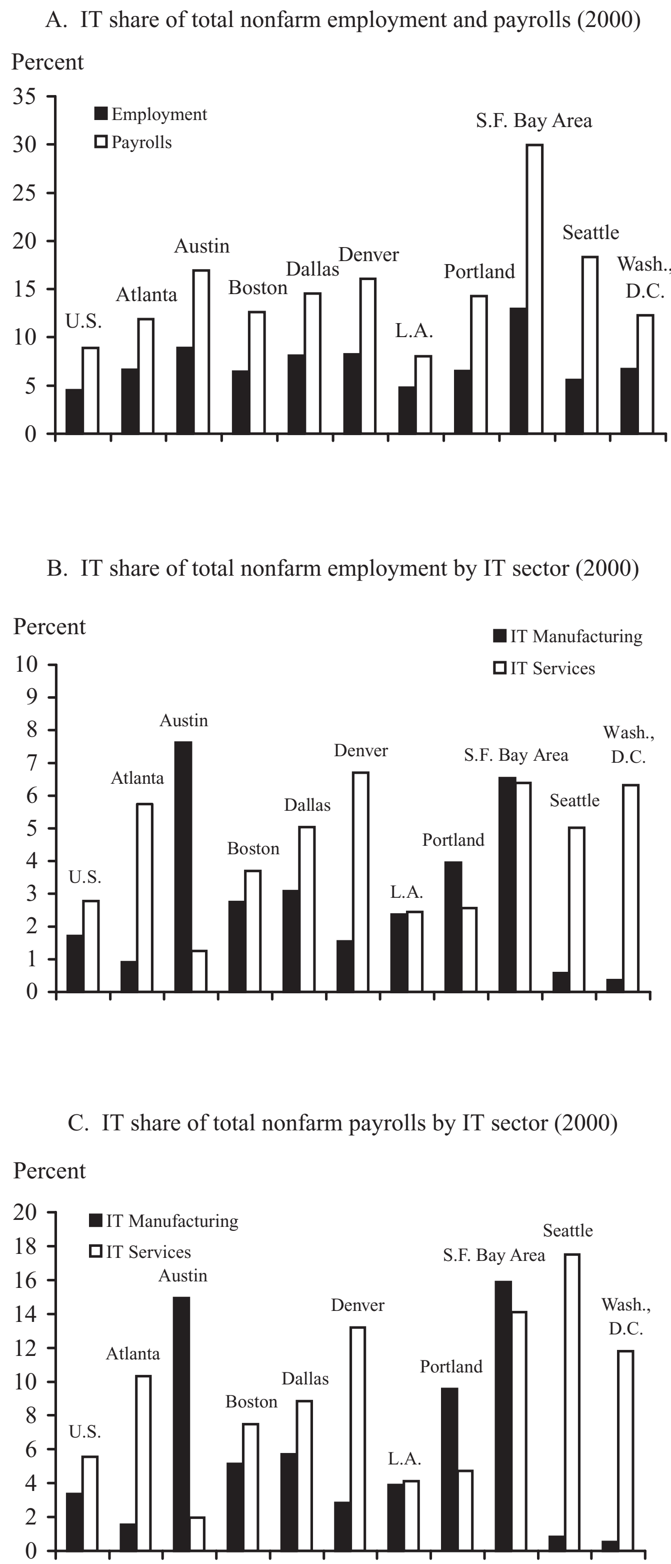
4.1. Concentration

As noted above (footnote 8), IT shares of employment and payrolls are the most commonly used measure of local IT concentration. We provide these figures for the year 2000, which corresponds to the peak of the IT boom.[9] Figure 1 (panel A) shows the IT shares of employment and wages in our IT centers. The IT shares in our centers are on average about one and a half times as large as the overall U.S. value (an all-metro value is not readily available in these data). The typical IT payroll share is about twice as large as the IT employment share, indicating that jobs in the IT sector pay about twice as much as the average wage in the nonfarm sector as a whole. The difference is largest for Seattle, with an IT wage share more than three times greater than the IT employment share, implying that IT jobs are compensated especially well there. The San Francisco Bay Area is a notable outlier with respect to the concentration of IT employment and wages in the area, with nearly 15 percent of regional employment and 33 percent of regional wages and salaries coming from the IT sector.[10]

Except for Los Angeles, all of the urban IT centers in our sample are more focused on IT industries than the nation. However, there is considerable diversity in the concentration on IT manufacturing or IT services, with most urban IT centers specializing in one or the other (Figure 1, panels B and C). For the U.S. as a whole, the IT services share of employment and wages is about 65 percent larger than the IT manufacturing share. The IT sectors in the Los Angeles area and the San Francisco Bay Area are notable for their relatively even distribution between IT manufacturing and IT services, which implies a greater focus on IT manufacturing than the nation as a whole. Austin and Portland also have a relative specialization in IT manufacturing; Atlanta, Denver, Seattle, and Washington, D.C., specialize in IT services; and Boston and Dallas have an IT manufacturing/services balance similar to that for the nation as a whole.

Among the key features of IT centers is their focus on innovation. One measure of innovative activity is spending on research and development. Data on R&D spending by firms with publicly traded stock are available from Compustat. Since Compustat does not provide data for individual establishments, values for R&D spending are based on the location of a firm's headquarters.[11] Figure 2,

FIGURE 1
MEASURES OF IT CONCENTRATION: EMPLOYMENT AND PAYROLL



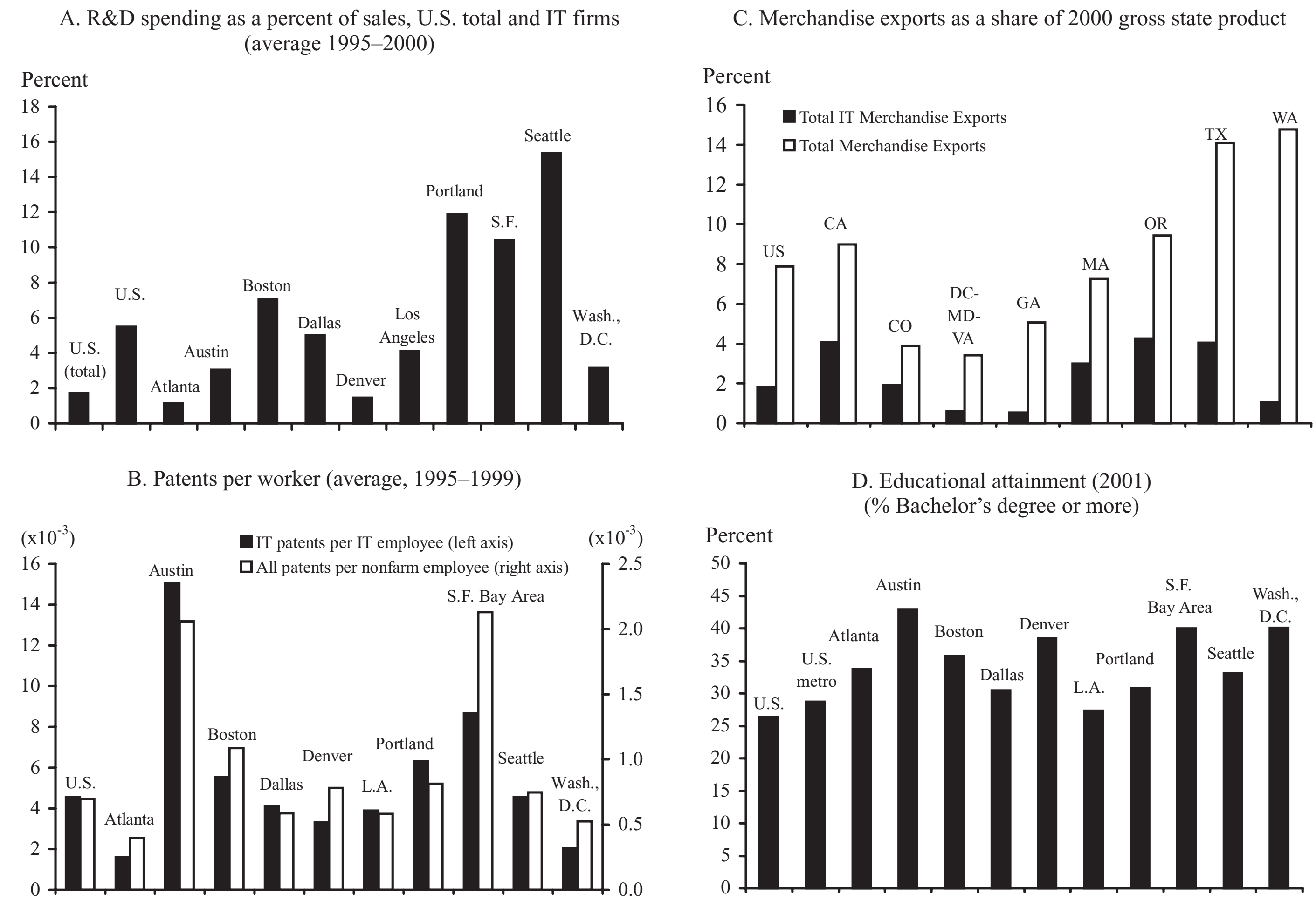
Source: Authors' tabulations using data from the U.S. BLS.

9. Through the year 2000, these data are provided under the Standard Industrial Classification (SIC) system. Beginning with data for the year 2001, NAICS has been used. Although data through 2002 have been released, the NAICS-based data are plagued by a high incidence of nondisclosed information for IT industry segments at the MSA level, and according to the BLS the 2002 data are based on incomplete information and are highly preliminary.

10. The IT shares for the San Jose MSA, which contains Silicon Valley, were especially large (28.5 percent of employment and 53.8 percent of payroll), although they have fallen since 2000.

11. The number of IT firms with information on R&D spending ranges from an average of about 10 to 15 firms per year in Austin up to about 300 firms per year in the San Francisco Bay Area.

FIGURE 2
OTHER MEASURES OF IT CONCENTRATION



Note: United States figures calculated from 1997–1999 data (panel A).
Sources: Authors' tabulations of data from Compustat (panel A), the U.S. Patent and Trademark Office and BLS (panel B), Global Trade Information Services (panel C), and the U.S. BLS (panel D).

panel A displays the ratio of R&D spending to sales, averaged over the years 1995–2000, for IT firms in the U.S., for firms across all industries in the U.S., and for IT firms headquartered in our sample of urban IT centers. As the figure shows, the R&D/sales ratio is higher among IT firms than among firms in all industries (first two bars). IT firms located in Portland, the San Francisco Bay Area, and Seattle reported R&D spending in the neighborhood of 12 percent of sales, a ratio approximately three times as large as for IT firms in the nation as a whole. IT firms headquartered in Boston also exhibit R&D/sales ratios higher than the national average for IT firms. The R&D tabulations suggest that these four metro areas devote substantial resources to innovative activity. By contrast, Atlanta, Austin, Dallas, Denver, Los Angeles, and Washington, D.C., all recorded lower R&D/sales ratios in IT than the nation.

The intent of private sector R&D spending is to innovate. The most commonly used measure of innovative outcomes is patents, for which we have data at the MSA level.[12] In Figure 2, panel B, we list tabulations of patents per employee, for all nonfarm industries and IT industries separately. Measured relative to employment, our IT centers are evenly split, with half exhibiting higher rates of IT patenting activity than the U.S. as a whole, and half exhibiting lower rates. Consistent with their relatively high R&D spending in IT, Portland and especially the San Francisco Bay Area exhibit very high rates of IT patents

12. These data are from the United States Patent and Trademark Office. Wilson (2003) documents the positive relationship between R&D and patents at the state level. However, patents also may be used as a strategic device for protecting other patents (see Bessen and Hunt (2003) for evidence regarding software patents).

per IT worker. Despite its relatively low private sector R&D spending, Austin is a notable outlier in regard to patents, with a rate of IT patents per IT worker over three times that in the nation as a whole and nearly double that for the next ranked MSA (the San Francisco Bay Area).[13] The Boston area also exhibits a relatively high rate of IT patenting relative to R&D spending. By contrast, Atlanta, Dallas, Denver, Los Angeles, Seattle, and Washington, D.C., all exhibit IT patenting rates equal to or less than that for the nation as a whole.

An additional feature of these IT centers is their reliance on exports. The U.S. is one of the world leaders in the export of technology products, and these IT centers play an integral role. Although detailed export data are not available at the MSA level, data for the states corresponding to our IT centers are available and provide adequate information on the export of IT merchandise.[14] To assess the role of merchandise exports in general, and IT merchandise exports in particular, for these states, we tabulated the shares of merchandise exports and IT merchandise exports in total state output (gross state product, or GSP) in the year 2000 (Figure 2, panel C). The share of all exports in state GSP varies substantially across these states, with some exhibiting values above the U.S. average and some below. However, most of these states exhibit IT export shares that are well above the national average, especially California, Oregon, and Texas.

Another important potential source of local cost advantages for IT production is the skill level of the workforce. As Figure 2, panel D shows, advanced educational attainment, measured by the percentage of individuals with a bachelor's degree or more, generally is higher in our urban IT centers than in the nation or in metropolitan areas nationwide. In Austin, the San Francisco Bay Area, and Washington, D.C., 40 percent or more of individuals have at least a bachelor's degree, compared to less than 30 percent in metropolitan areas nationwide. Only the Los Angeles area exhibits a lower share of college graduates than the U.S. metro average.

Finally, it also is important to acknowledge variation in the financial environment. In particular, given the rapidity and risk associated with change in the IT sector, venture capitalists, who focus on the financing of start-ups, have an important role to play in the growth of IT centers (see Hellman and Puri 2002 for evidence regarding their role). Although a breakdown of venture capital (VC) spending is not available at the MSA level, regional figures are available. In general, these data show that through 2000, venture capital spending (all industries) was heavily dominated by the San Francisco Bay Area, which is well known for its extensive array of VC firms. Data for 2001 and 2002 show a sharp drop in overall VC spending, but the San Francisco Bay Area still received about one-third of the total. Overall, these data suggest that, while VC spending has played an important role in the development of IT, a disproportionate share of the VC activity has been in the San Francisco Bay Area.

4.2. Diversification

As discussed in Section 2, the economic literature on the formation and growth of industy clusters suggests that diversification may be an important attribute of urban IT centers. The degree of specialization within the IT sector varies across our IT centers. We already have noted substantial differences across our IT centers in regard to the respective shares of IT manufacturing and IT services (see Figure 1). More precise measurement of the degree of specialization/diversity in the IT sector can be obtained through the use of the inverse Herfindahl index: higher values of the index indicate a greater degree of diversity, as measured by the dispersion of an indicator (employment, patents, etc.) across subsectors within IT.[15] In Table 3, we list inverse Herfindahl indexes tabulated based on the distribution of IT employment, IT payrolls, and IT patents. Los Angeles and Dallas exhibit the highest degree of IT sector diversity, as measured by the distribution of employment, wages, and patents across IT subsectors. In fact, IT sector diversity in the Los Angeles area is even higher than that for the nation as a whole. In regard to employment and payrolls, the San Francisco Bay Area and Portland each exhibits relatively high degrees of IT diversity. Seattle, Washington, D.C., and Boston exhibit relatively low diversity, while Atlanta, Austin, and Denver fall in the middle of the distribution. A generally similar pattern is evident in regard to the diversity of IT patents. However, Boston shows a relatively high de-

13. Several of these urban IT centers also have a substantial concentration of IT R&D and patenting activity emanating from universities and government-funded research centers. The San Francisco Bay Area stands out in this regard, with two major research universities (University of California, Berkeley, and Stanford University) and several major government-funded research centers that engage in substantial IT-related research.

14. Available information suggests that our urban IT centers account for the majority of IT exports for their states. Data on services exports are not available at the state level.

15. In our setting, the Herfindahl Index (H) is defined as $\sum_i s_i^2$, where s_i equals the share of IT subsector i in total IT employment (or payrolls, patents, etc.). When measured in inverse form H^{-1}, the value of this statistic increases as the number of subsectors increases and the distribution of employment approaches complete uniformity across subsectors (complete uniformity means that s_i equals $1/n$ for every subsector, where n equals the number of subsectors).

TABLE 3
IT SECTOR DIVERSITY
(INVERSE HERFINDAHL INDEXES, OR H^{-1})

Region	Employment H^{-1}	Employment Relative rank	Wages H^{-1}	Wages Relative rank	Patents H^{-1}	Patents Relative rank
Atlanta	3.0	(6)	2.8	(6)	4.7	(8)
Austin	3.5	(5)	3.1	(5)	4.0	(10)
Boston	2.8	(8)	2.5	(8)	6.5	(3)
Dallas	4.3	(2)	4.1	(2)	7.0	(2)
Denver	2.8	(7)	2.8	(7)	6.3	(5)
Los Angeles	6.0	(1)	5.7	(1)	7.9	(1)
Portland	3.9	(3)	3.3	(4)	5.3	(6)
S.F. Bay Area	3.7	(4)	3.6	(3)	6.4	(4)
Seattle	2.2	(9)	1.4	(10)	4.7	(9)
Washington, D.C.	1.8	(10)	1.7	(9)	5.3	(7)
United States	4.8	—	4.3	—	7.2	—

Source: Authors' tabulations using data from the U.S. BLS and U.S. Patent and Trademark Office.

gree of IT diversity in patents relative to employment and wages, while IT patent diversity in Austin is comparatively low.[16]

It is likely that areas with high IT sector diversity are well positioned to respond to emerging IT product demand trends. Of course, diversity is not the only determinant of success in IT: Seattle's economy has surged largely based on the success of Microsoft, which is contained within the narrow software segment of the IT industry. But IT centers such as Los Angeles, Dallas, the San Francisco Bay Area, and perhaps Portland are likely to benefit from the diversity in their IT industrial base, which allows them to respond flexibly to changes in IT production and demand conditions.

In the next sections we consider how the concentration of IT production and the diversification among IT industries contributed to the run-up and subsequent downturn in employment in our sample of urban IT centers.

5. IT Boom and Bust

5.1. National IT Employment

Before considering the impact of the national IT boom and bust on urban IT centers, it is useful to review the basic trends in U.S. IT employment associated with the run-up and subsequent downturn in IT investment. Between 1995 and 2000, business investment in IT goods and services increased at an average annual rate of 20 percent per year, fueling rapid growth in output, employment, and earnings among IT companies.[17] Although most IT sectors expanded rapidly during this period, growth in some sectors was especially brisk. Figure 3 (panels A and B) show the expansion of national IT manufacturing and services employment by detailed sector.[18] The first thing to note is that employment in IT services expanded much more rapidly than employment in IT manufacturing. IT services employment in the U.S. grew at an average annual rate of 8.5 percent from 1995 through 2000, while IT manufacturing employment expanded by 1.7 percent at an average annual rate. Nearly every subsector of IT services exhibited more rapid employment growth than IT manufacturing, with scientific research and development services being the sole exception.

Within the services sector, employment growth was most rapid among software publishers, Internet service providers, and computer systems design firms, with average annual growth rates of 11 to 15 percent. Employment growth in telecommunications and business and technical support was less extraordinary, but very robust. Within IT manufacturing, employment growth for makers of semiconductors and electronic components and makers of magnetic media expanded job counts most quickly, by just over 4 percent per year on average. Employment growth among makers of computers and communications equipment was much less rapid, averaging 0.6 percent and 2 percent per year, respectively. Unlike the IT services sector, two subsectors of IT manufacturing—audio and video equipment and electronic instrument manufacturing—shed jobs during the expansion.[19]

Following more than five years of double-digit growth, business investment in IT products and software slowed in 2000, damped by uncertainty in the national economy, the

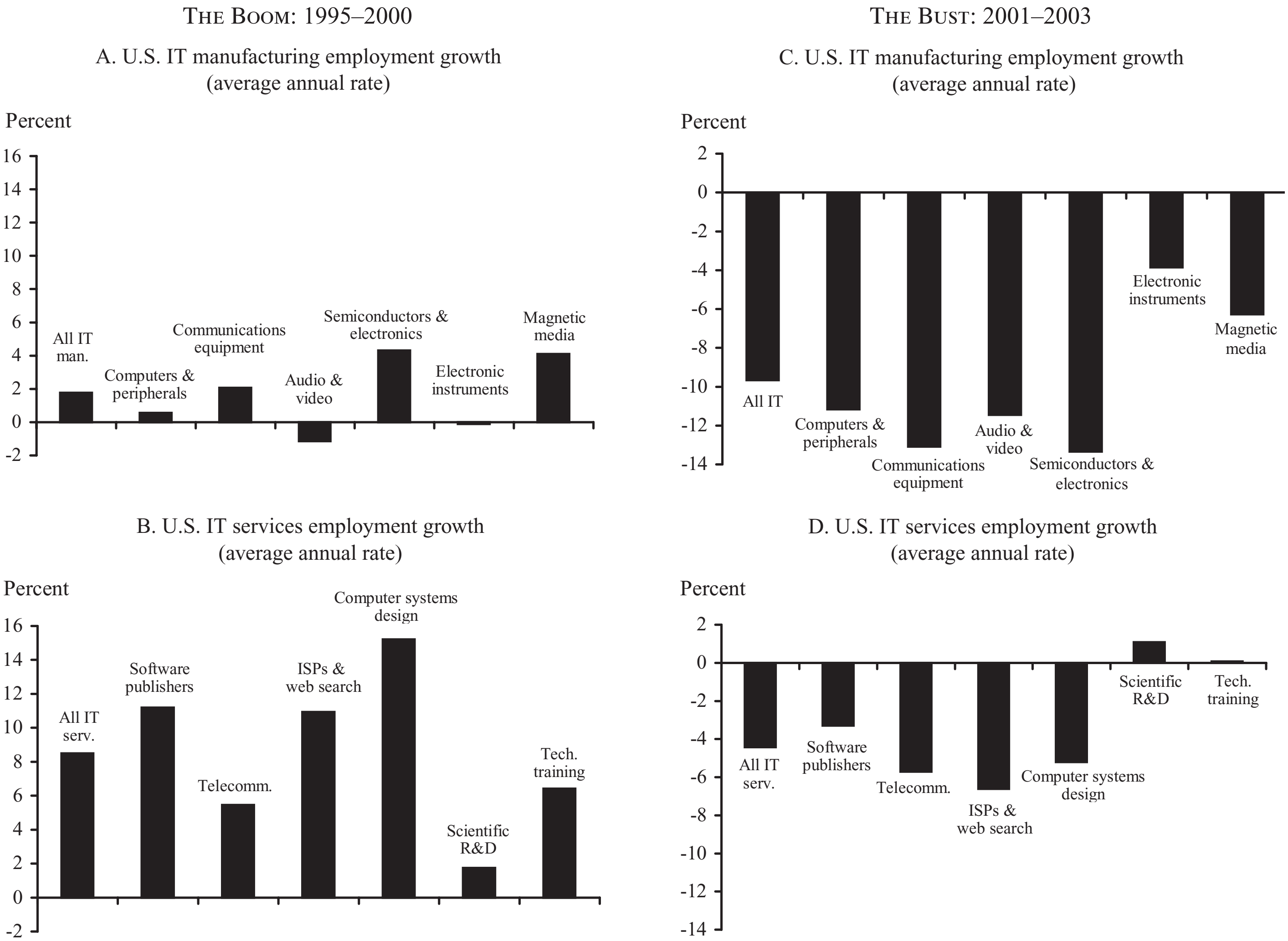
16. The employment and payroll calculations rely on SIC data at the four-digit level, from the BLS CEW program. Although these calculations are affected by nondisclosure restrictions for industry categories with a small number of establishments, it is likely that nondisclosed categories are small and therefore have only a limited influence on the diversity calculation. Nondisclosure is not an issue for the patents data. The patents calculation relies on a breakdown of IT patents into eleven subcategories obtained from the NBER Patents Citation Data File (see Hall, Jaffe, and Tratjenberg (2001)).

17. Consumer demand for IT products also grew rapidly during the period, continuing a trend that began at the end of the early 1990s recession.

18. The panels display IT manufacturing and IT services as previously defined, with a breakdown into their primary subsectors (based on the 2002 NAICS).

19. These are areas of manufacturing that reportedly have faced the most intense import competition.

FIGURE 3
U.S. IT EMPLOYMENT, BOOM AND BUST



Note: November 2003 is the last month of data used for all categories.
Source: Authors' tabulations using data from the U.S. BLS.

dot-com and telecommunications crash, and overinvestment by businesses in IT goods.[20] The abrupt slowdown in business investment in IT had a pronounced impact on overall demand for IT products, reducing orders, shipments, output, and employment at most IT firms. However, just as there was heterogeneity in the expansion, the IT bust also was felt to varying degrees across more detailed IT sectors (Figure 3, panels C and D). Job losses in IT manufacturing were especially pronounced, with employment falling by nearly 10 percent per year on average during the period from January 2001 through November 2003. Makers of semiconductors and other electronic components, as well as communications equipment manufacturers, shed jobs even faster, with reductions of more than 13 percent per year. Makers of electronic instruments and magnetic media were least negatively affected by the drop in business investment; those sectors lost jobs at rates of 3.9 and 6.2 percent, respectively.

IT service providers fared slightly better, cutting jobs at about half the pace of IT manufacturers; employment in IT services contracted by 4.4 percent per year on average from 2001 through November 2003. Consistent with the dot-com crash, Internet service providers and web search and portal firms experienced the most rapid declines, shedding jobs at an average annual rate of 6.6 percent. Telecommunications providers and computer systems and design firms also reduced employment, cutting jobs by 5.7

20. See Doms (this issue) for a more detailed treatment of the determinants of the IT investment bust.

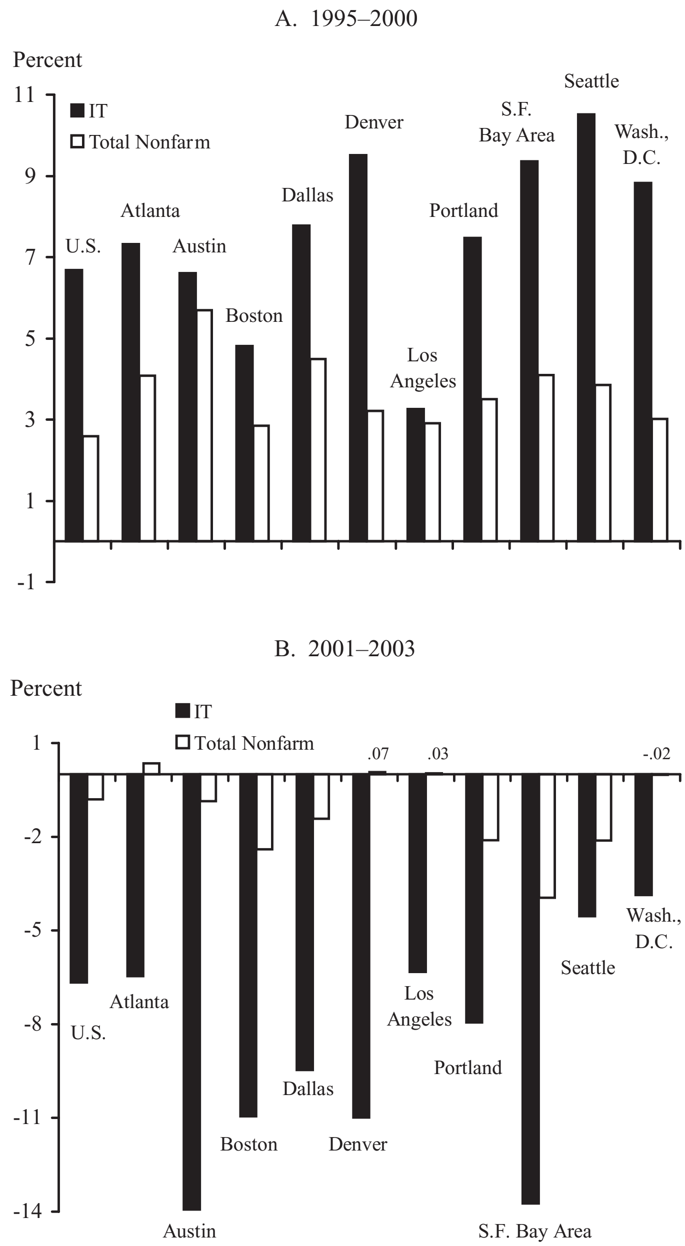
and 5.2 percent per year, respectively. Software publishers, scientific research and development firms, and business and technical support companies were the least affected by the downturn, with the latter two subsectors adding jobs during the period.

The pervasiveness and magnitude of the job changes in the national IT sector portend similar patterns for each of our urban IT centers. That said, the heterogeneity of the gains and losses within the IT sector, and the different specializations evident in our urban IT centers, suggest that the impact of the boom and bust may vary substantially across our sample.

5.2. IT Employment in Urban IT Centers

Figure 4 displays the annual rate of employment growth for our MSAs and the nation, listed separately for the IT sector and for total nonfarm jobs. The top panel lists growth rates during the IT boom, from 1995–2000, and the bottom panel lists growth rates from the beginning of the recession in 2001 through 2003.[21] As in the nation, IT employment growth was quite rapid in our sample of urban IT centers. With the exception of Boston and Los Angeles, IT employment growth in our urban centers was at or above the national pace. For urban centers with large concentrations of IT services, including Denver, the San Francisco Bay Area, Seattle, and Washington, D.C., growth was especially rapid, averaging over 9 percent per year during the boom.[22] In keeping with the slower growth of IT manufacturing employment nationally, urban IT centers dominated by manufacturing (Austin and Portland) saw IT employment expansion at a rate nearer the U.S. average. The relatively slow growth in IT employment in Boston and Los Angeles (compared to the U.S.) likely owes to product specializations in those areas (see Table 1). Boston specializes in computers, medical devices, and software production; nationally, employment in the computer industry grew slowly during the expansion (0.6 percent per year), while electronic instrument manufacturing, which includes medical devices, fell (see Figure 3, panel A). Similarly, Los Angeles specializes in household audio and video equipment manufacturing, which shed jobs during the boom.

FIGURE 4
EMPLOYMENT GROWTH (AVERAGE ANNUAL RATE)



Source: Authors' tabulations using data from the U.S. BLS.

Relatively rapid growth in IT employment was matched by relatively rapid growth in total nonagricultural employment in our urban IT centers. Indeed, all of the urban IT centers experienced more rapid growth in total employment from 1995 through 2000 than did the nation. Although no clear causal relationship between IT employment growth and total employment growth can be drawn

21. These calculations are based on monthly employment data from the BLS Current Employment Statistics (CES) program. The degree of industry detail available in these data is somewhat limited, so our definition of IT services in these data are less precise than it is in our analyses based on other data (we have nearly complete data for IT manufacturing). This is especially true in the smaller MSAs; for example, using these data, the IT services sector in Austin is limited to telecommunications services. We assume that these restricted definitions produce series that are representative of patterns in IT service industries more generally.

22. See Figure 1, panel B, for a breakdown of IT manufacturing and IT services employment shares in our urban IT centers.

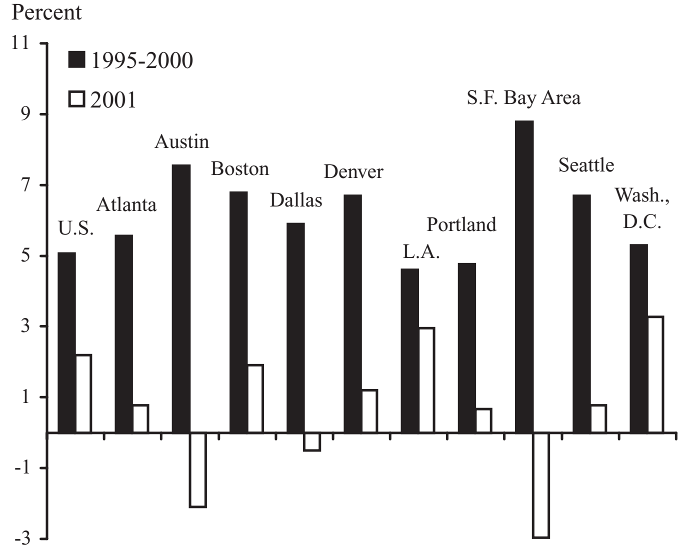
from the figure, the correlation suggests that rapid increases in IT employment spilled over to other sectors of the economy. Given the relatively high wages paid to workers in the IT sector, the spillovers to employment may have been large.

Just as the run-up in IT investment disproportionately benefited many urban IT centers, its collapse moved several into recession. In the extreme, Austin and the San Francisco Bay Area shed IT jobs at a nearly 15 percent annual pace from January 2001 through November 2003 (Figure 4, panel B). Both areas, especially Austin, were highly exposed to the IT manufacturing downturn. The San Francisco Bay Area also was quite exposed to the dot-com collapse and the loss of Internet service and web portal jobs (see Figure 3, panel D). The downturn in telecommunications had a negative effect on Dallas and Denver, homes to makers of telecommunications equipment and providers of telecommunications services. Both areas shed jobs rapidly from 2001 through 2003, reducing IT employment at annual rates of 9.5 and 11 percent, respectively. The Portland area, which specializes in semiconductor manufacturing, suffered a substantial hit due to the pronounced downturn in that sector. In areas more focused on IT services other than communications or Internet support—Atlanta, Seattle, and Washington, D.C.—IT job losses were less severe, occurring at or below the national pace.

As was true in the run-up, the downturn in IT employment in our urban centers is reflected in the total employment growth numbers. However, unlike the run-up, when the IT boom helped propel growth in total employment in our urban centers above the national average, the downturn had a more mixed effect. To be sure, several of the IT centers experienced contractions in total employment in excess of the national average: these include Boston, Dallas, Portland, the San Francisco Bay Area, and Seattle. But Atlanta, Denver, Los Angeles, and Washington, D.C., fared relatively well compared to the U.S., with total employment remaining essentially flat during the period. This suggests the presence of positive factors that offset the loss of IT jobs, such as population growth or stimulative effects from sources such as the federal government.

As already discussed, IT jobs tend to be high-wage, and as such gains or losses of IT jobs are likely to have large impacts on total personal income, even if the impact on total employment is offset by other factors. Figure 5 shows changes in income per capita, which reflect growth in living standards. With the exceptions of Los Angeles and Portland, each of the IT centers saw more rapid growth in income per capita during the 1995–2000 period than did the nation as a whole. Subsequently, all of the IT centers except Los Angeles and Washington, D.C., saw slower income growth than the nation in 2001. The San Francisco Bay Area is an extreme case on both counts, having seen extremely rapid income growth during the boom followed by a 3 percent drop in 2001. Austin also saw an especially sharp turnaround in income growth. Of interest is the fact that in most of our IT centers, personal income growth slowed but remained positive. This was true even for centers that saw contraction in total employment as well as IT employment.

FIGURE 5
PERSONAL INCOME PER CAPITA (AVERAGE ANNUAL CHANGE)



Source: Authors' tabulations using data from the U.S. BEA; data available only through 2001.

These results bring out two key points. First, the detailed composition of the IT sector played an important role in determining the patterns of growth and decline in urban IT centers during the boom and bust. Second, while developments in IT affect our IT centers, both positively and negatively, they are not the only factors contributing to the economic vitality of the regions, with several urban IT centers benefiting from factors that offset the IT bust during the past few years.

6. Empirical Determinants of Urban IT Growth

6.1. Business Investment Spending on IT

Thus far, we have examined the characteristics of our urban IT centers and assessed their links to the boom-and-bust dynamics of the 1995–2003 period. These unidimensional comparisons point to considerable heterogeneity among urban IT centers in terms of performance during the national IT run-up and the subsequent downturn. We now

Box 1

Models of Business Investment in IT and Regional IT Employment Growth

We estimate multivariate descriptive relationships between regional IT employment growth and growth in national business investment in IT, controlling for growth in other national variables.

Our basic specification takes the following form:

$$ITEmploy_t = \alpha + \beta ITInvest_t + \gamma X_t + \varepsilon_t,$$

where $ITEmploy_t$ and $ITInvest_t$ are the quarterly annualized growth rates of IT employment and national business investment in IT, X_t is a vector of national control variables, α, β, and γ are coefficients to be estimated, and ε_t is a normally distributed error term. The control variables include quarterly annualized growth in total U.S. nonagricultural employment, real U.S. GDP, and personal consumption expenditures on computers, as well as a time trend. The models are estimated separately for the U.S. and each of our ten regional IT centers. Standard errors in all regressions are corrected for heteroskedasticity and autocorrelation.

The IT business investment series and the personal consumption expenditures on computers series come from the Bureau of Economic Analysis (BEA). We use series expressed in real dollars.

Employment data are from the BLS CES employment file. IT employment is defined as specified in Section 3.

The investment series can be decomposed into investment in computers and peripherals, other IT equipment, and software. We use these decompositions to estimate the following specification:

$$ITEmploy_t = \alpha + \beta_1 ITInvcomp_t + \beta_2 ITInvother_t + \beta_3 ITInvsoft_t + \gamma X_t + \varepsilon_t.$$

We also include a measure of the IT import share in some regressions. That ratio is computed as nominal imports of IT goods divided by nominal sales of IT goods. Data for the calculation come from the BEA.

turn to an investigation of the factors that are important to explaining these differences and link the results to the growth potential going forward. We first consider the linkages between national business investment in IT and growth in urban IT centers. Since the run-up in business investment in IT defined the IT boom and the contraction in these investments was a major factor in the IT bust, it is a potentially important factor in explaining the diversity of outcomes among urban IT centers.

Before considering a multivariate model of the relationship between national business investment in IT and IT employment in our urban IT centers, it is useful to pin down their association using simple causality tests. We use the Granger causality test (Granger 1969) to quantify the extent to which information about business investment patterns strengthens predictions of IT employment in our urban centers, and vice versa. Specifically, for each urban IT center we test whether annualized quarterly growth of business investment in IT equipment and software Granger-causes annualized quarterly growth in IT employment, and vice versa.[23] We perform the analysis using one to four lags of both variables in the test.

The results confirm the importance of national IT investment in predicting urban IT employment, with increases (decreases) in IT investment leading increases (decreases) in IT employment. Growth in IT investment Granger-causes IT employment growth in each of our urban IT centers.[24] Importantly, there is little evidence that the relationship works the other way, i.e., changes in urban IT employment do not tend to lead changes in national IT investment. IT employment growth Granger-causes growth in IT business investment in just one urban center—the San Francisco Bay Area.[25]

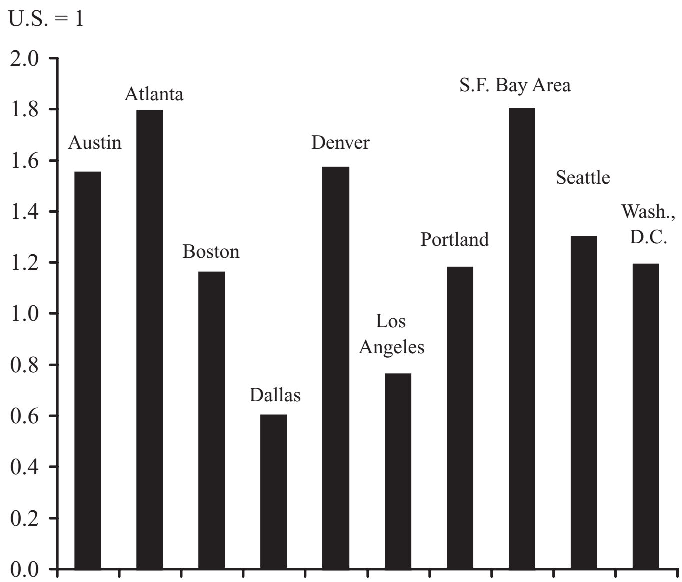
To analyze these relationships more completely we estimate multivariate models of urban IT employment growth and growth in U.S. investment in IT equipment and software for each of our urban IT centers. Our basic specification estimates the relationship between quarterly annualized growth in IT employment and quarterly annualized growth in business investment in IT equipment and software, controlling for national employment growth in all sectors, real U.S. GDP growth, real consumer expenditures in computers, and a time trend. We augment this basic specification by decomposing total IT investment into investment in computers, investment in other IT equipment, and investment in software. The period covered is 1990 to 2003 (September). Box 1 provides details of these regressions.

23. Contrary to its name, tests for Granger causality do not tell us whether one variable is causally related to another variable. In our context, the test simply indicates whether changes in national business investment in IT help predict changes in IT employment in our urban IT centers and vice versa.

24. This statement holds at the 5 percent level of statistical significance.

25. This is true at a significance level of 10 percent but not at 5 percent.

FIGURE 6
IT EMPLOYMENT AND IT INVESTMENT
RESPONSE OF URBAN CENTERS RELATIVE TO U.S. TOTAL



Note: All estimated coefficients are significantly different from zero and the U.S. baseline coefficient.
Source: Authors' tabulations using data from the U.S. BEA and BLS. See Box 1 for details.

TABLE 4
IMPORTANCE OF IT INVESTMENT
TO REGIONAL IT EMPLOYMENT GROWTH, BY TYPE

	Computer investment		Other IT equipment investment		Software investment	
Region	Signif.	Relative to U.S.	Signif.	Relative to U.S.	Signif.	Relative to U.S.
Atlanta			x	>	x	>
Austin	x	>	x	>	x	>
Boston			x	<	x	>
Dallas						
Denver			x	>		
Los Angeles					x	>
Portland			x	>		
S.F. Bay Area			x	>	x	>
Seattle			x	>	x	>
Washington, D.C.			x	>	x	>

Note: x indicates that the coefficient is significantly different from zero and significantly different from the U.S. baseline coefficient.
Source: Authors' tabulations using data from the U.S. BEA and BLS. See Box 1 for details.

The results indicate that growth in business investment in IT equipment and software has a statistically significant effect on IT employment growth in the U.S. and in each of our ten urban IT centers. For the U.S. as a whole, a doubling of the annual rate of growth of IT investment—for example, from 5 to 10 percent—produces about a 30 percent increase in the rate of growth of IT employment. Based on the mean relationship between IT employment and IT investment spending in the U.S. from 1990 through 2003, an increase in the rate of growth of IT investment from 5 to 10 percent would increase the rate of IT employment growth about a quarter of a percentage point, from 0.66 to 0.93 percent (27 basis points).[26]

In general, compared to the nation as a whole, the response of IT employment to national IT investment spending is even larger in our urban IT centers, with the notable exceptions of Dallas and Los Angeles (Figure 6).[27] IT employment growth in the San Francisco Bay Area and in Austin are especially responsive to changes in national IT investment spending, with coefficients 1.8 times as large as the U.S. This means that a doubling of IT investment nationally would produce about a 50 basis point increase in IT employment growth in Austin and the San Francisco Bay Area. The relative importance of IT investment is more muted in the other IT centers but remains higher than for the U.S. as a whole. IT employment in Dallas and Los Angeles is less responsive to changes in business investment in IT than the nation. While this is not entirely predictable, it is consistent with their relative dependence on demand for consumer IT products as compared to business IT products (not shown). For example, IT employment in Dallas and Los Angeles is more than twice as responsive to changes in personal consumption expenditures on computers than is the nation. The next most responsive urban center is Austin, with a value about 1.2 times that of the U.S.

Given the differences in product specialization across IT centers, it is instructive to decompose IT investment into its component parts—computer investment, investment in other IT equipment, and software investment. Table 4 lists the results of these analyses, which rely on the same regression framework as above. All reported results are statistically different from zero and statistically different from the relevant U.S. coefficient. The impact of business investment in computers on IT employment is statistically significant in Austin but not in other MSAs. Investment in other IT equipment is the most influential category, statistically significant in every IT center except Dallas and Los Angeles and, in general, more important in urban IT centers than it is for the nation as a whole. Growth in software

26. The average annual rate of U.S. IT employment growth over the period was 1.2 percent.

27. Note that the coefficients on IT investment in our urban IT centers are all significantly different from zero and significantly different from the U.S. coefficient.

investment has a significant impact on IT employment growth in Atlanta, Austin, Boston, Los Angeles, the San Francisco Bay Area, Seattle, and Washington D.C., and the magnitude of these effects is larger than in the nation as a whole.

The results of these regressions support the notion that, in general, the IT sector in urban IT centers is more responsive to national changes in IT investment than is the IT sector for the nation as a whole, even when controlling for other factors. Austin and San Francisco stand out as areas especially responsive to changes in IT investment growth, while Dallas and Los Angeles are notable exceptions.[28]

6.2. Overseas Production

The analysis of the preceding subsection indicates that, as the economy recovers and IT investment growth accelerates, IT employment and output growth in our set of IT centers should rebound. However, the impact of rising IT investment is likely to vary across urban IT centers. Moreover, there is no guarantee that the past relationship between IT investment and IT employment will continue into the future, given factors that could weaken or alter this relationship.

One such factor—indeed, one of the key emerging trends evident in the U.S. IT sector—has been an increasing reliance on overseas production facilities. The shift has mainly been toward East Asia, especially China, in the form of increased foreign investments by U.S. IT companies and increased reliance on production outsourcing to foreign IT companies. This shift was especially pronounced in 2002, as the locus of demand growth for IT products shifted towards East Asia and U.S. IT firms facing prolonged weakness in overall product demand were forced to focus increasingly on low-cost production opportunities; the result was a sharp increase that year in the U.S. merchandise trade deficit for IT products (U.S. Department of Commerce 2003, Valletta 2003).

Although this overseas shift poses a challenge to domestic IT producers who cannot respond effectively to the changing locus of production, it likely is a positive development for the U.S. economy more generally. The successful reliance on lower-cost production techniques reduces prices for IT products sold in the U.S. Moreover, some U.S. IT firms are able to capitalize on these trends, increasing their overseas exports, reducing costs, and improving their own production processes, leading to improvements in their bottom lines.

It is likely that our IT centers have varying degrees of exposure to this overseas shift, depending on their degree of access to East Asian and other overseas markets (for example, due to the product mix of their IT production base, geographic location, cultural ties, etc.). Continuing with the analysis reported in the preceding subsection, we investigate the relative responsiveness of urban IT employment growth to changing patterns of IT trade. To measure the IT trade balance, we use a variant of a common measure of import competition known as the "import penetration ratio." In particular, we measure the U.S. net trade balance in IT products as the ratio of nominal IT imports of manufactured goods to nominal U.S. sales (domestic and export) of IT manufactured goods. This ratio fluctuates with the business cycle and trends in the value of the dollar, but it reflects more generally the U.S.'s relative reliance on imports in the domestic IT sector. The value of this variable increases with IT imports and decreases with IT exports and domestic sales, and, as such, reflects changes in the full range of domestic and overseas production and sales conditions (outsourcing, increased foreign direct investment by U.S. IT firms, declining domestic demand for IT products, etc.). To gauge the responsiveness of IT employment in our IT centers to the IT trade balance, we include this variable in a regression with our control variables (specified in Box 1) and our measure of growth in total IT investment. As in the previous regressions, the results are reported relative to a baseline U.S. regression coefficient.

The results (not displayed) suggest that imports relative to sales of IT goods do influence the pace of IT employment growth, although the magnitude of the effect is quite small. For example, a doubling of the relative imports variable, which occurs periodically in the sample, reduces IT employment growth in the U.S. by about 0.05 percentage point. Relative to this baseline, Austin is the most exposed to import competition; there, a doubling of the import penetration ratio shaves about 0.1 percentage point off IT employment growth. The other IT centers that are more responsive to IT import penetration than the U.S. as a whole are Denver, Seattle, and the San Francisco Bay Area.

These effects of the IT trade balance are all small. However, because this regression analysis refers to the entire period, 1990–2003, it may understate the long-term impact of the trend towards overseas production, since this trend is a relatively recent phenomenon that may exhibit an increasing influence in the data as time passes. Some observers have expressed concern that U.S. IT pro-

28. Available data do not enable us to examine the responsiveness of IT output growth (as opposed to employment growth). However, despite noticeable differences in productivity levels across urban IT centers, productivity growth in IT has been relatively uniform at the industry/region level. This suggests that IT output growth is likely to follow the same patterns as IT employment growth.

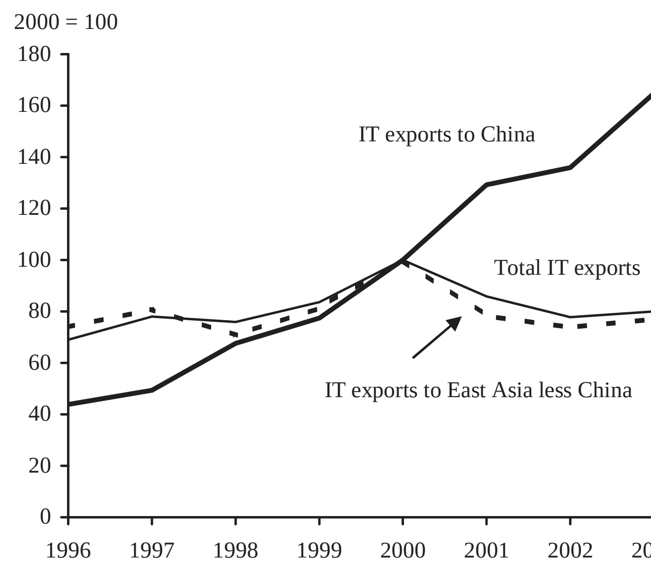
duction activity, and especially IT employment, is beginning a prolonged period of decline due to this production and demand shift. For example, as argued in a report commissioned by the Semiconductor Industry Association (Howell et al. 2003), China's recent success in expanding its microelectronics industry may increasingly draw capital, skilled labor, and R&D resources away from the U.S. IT sector. This in turn may serve to erode the research and production base that in the past has helped to maintain the U.S.'s competitive edge in worldwide IT markets.[29]

Although we cannot rule out the possibility that such developments will lead to a long-term decline in the U.S. IT sector, past experience and other trends suggest that it is not likely to occur. First, the competitive advantage enjoyed by the U.S. IT industry is based on the ability to identify and develop innovative products that spur worldwide growth in the IT industry. By contrast, the recent shift towards overseas production, especially to China, largely reflects normal product-cycle dynamics, in which the diffusion of technology enables less-advanced countries to manufacture products that initially were manufactured only in advanced countries. China's IT sector focuses primarily on assembly of less-advanced products at low cost, which does not threaten U.S. dominance in leading-edge technology and innovative products at this point. That dominance is likely to continue once domestic demand for IT products enjoys the expected sustained cyclical upswing. In particular, strong productivity gains in the U.S. economy over the past few years and continued R&D spending by IT companies suggest that the innovative process is alive and well in the U.S. IT industry.

In addition, during the last few years, as the U.S. IT merchandise trade balance has deteriorated, the IT services trade balance has improved markedly. Data from the U.S. Department of Commerce (2003) indicate that the U.S. trade surplus in IT services increased from \$0.5 billion in 1997 to \$8.4 billion in 2002 (exports of \$14.3 billion, imports of \$5.9 billion). Although the 2002 figure makes only a small dent in an estimated IT merchandise trade deficit of \$43.3 billion that year (authors' calculations), the trend toward an increased IT services trade surplus suggests that the U.S. maintains an edge in some areas of IT service provision vis-à-vis the rest of the world. This trend runs counter to the common perception of net losses in U.S. IT services jobs to foreign locations and companies in recent years. Although the overseas movement of some IT service jobs—such as call centers—is undeniable, the growing U.S. edge in high-value services, such as sales of software and data processing services, substantially offsets the loss of lower-value activities.

Which IT centers can best respond to these changes? The overseas shift of IT manufacturing presents opportunities as well as challenges. In particular, despite the sharp increase in U.S. IT merchandise imports from China in recent years, U.S. IT merchandise exports to China have grown rapidly as well; this has been true even during the last few years, when U.S. IT exports in general, including to the rest of East Asia, fell substantially (Figure 7).[30] But access to IT export markets varies across our set of urban IT centers. Figure 2, panel C, discussed earlier, shows that the states containing the IT centers of Austin (Texas), Boston (Massachusetts), Portland (Oregon), and the San Francisco Bay Area (California) have an especially high share of IT exports in their economic base. Each of these states also has seen increased IT exports to China between 2000 and 2003 (through the third quarter), suggesting that

FIGURE 7
UNITED STATES IT EXPORTS (GOODS)



Source: Authors' tabulations using data from Global Trade Information Services.

29. As noted in the SIA report (Howell et al. 2003), China's success has been achieved in part through preferential tax policies that favor semiconductor makers who locate facilities in China. This raises potential issues for trade negotiations, especially given China's recently acquired status as a member of the World Trade Organization.

30. The IT production process exhibits complex international linkages, with substantial cross-border flows of intermediate and final products. The content of U.S. IT exports to China and U.S. IT imports from China suggests a pattern whereby U.S.-made IT components such as microprocessors are shipped to China, assembled into final products, and then sold in the U.S. As such, expanding IT production in China represents an opportunity for some U.S. IT producers.

its respective urban IT center may have benefited from the expansion of China's IT manufacturing base (data not shown).

7. Growth Prospects

Conditions in the U.S. IT industry improved substantially in 2003 and early 2004. Production and sales moved up for a wide range of IT products; for example, according to the Semiconductor Industry Association, worldwide sales by U.S. chip makers rose 18.3 percent in 2003, with especially strong increases evident in the second half of the year. Moreover, following several years of declines, business investment spending on IT equipment and software expanded rapidly in 2003, rising 21 percent for the year, with growth accelerating as the year progressed (to 25 percent at an annual rate in the second half).

These developments bode well for the performance of the urban IT centers discussed in this paper. In particular, our statistical analyses suggest that the IT sectors of these cities in general are highly responsive to business investment spending at the national level. Moreover, despite significant deterioration in the U.S. IT trade balance in 2002, statistical analyses and additional data suggest that performance in our set of urban IT centers is relatively insensitive to these changing trade flows, with companies in many areas actually benefiting substantially (through increased export demand) from the increase in overseas IT production activity.

More generally, each of the urban IT centers that we have examined possesses features that will enable it to capitalize on the more general recovery taking hold in the IT industry. The San Francisco Bay Area, by virtue of the size, diversity, innovative performance, and unique financing of its IT sector, is well-positioned to maintain its leadership role in the IT industry, despite being among the areas hardest hit by the IT downturn. Although Boston experienced a somewhat muted IT boom compared to other IT centers, it remains a location for diverse innovative activities, making it a likely participant in any IT resurgence. Portland relies heavily on IT manufacturing and consequently was hit hard by the downturn in that sector; however, the level and diversity of innovative activity (patents) in Portland is high, which leaves it well-situated to respond to changes in production technology and product demand in the IT industry.

The future for IT in Austin and Denver may be more challenging. Both were hit hard by the IT downturn and exhibit a degree of specialization in, respectively, IT manufacturing (computers) and services (telecommunications) that may hamper somewhat their ability to capitalize on emerging trends in IT product demand. However, patent data suggest a high rate of specialized innovation in Austin, which may help keep that area at the forefront of its IT industry niche.

In the remaining urban centers, the IT downturn was less severe, making the return to stability less difficult. In the Washington, D.C., area and Seattle, continued growth in demand for IT services prevented the large declines in IT employment recorded in other urban IT centers. In Seattle, the presence of a major software industry leader, Microsoft, helps ensure its place in the recovery of IT. Atlanta, Dallas, and Los Angeles were among the most insulated from the ups and downs of the IT investment cycle, with IT employment in Dallas and Los Angeles being notably less responsive to changes in business investment in IT than the nation as a whole. The diversity of IT activity in these areas and their relatively well-educated workforces (except in Los Angeles, which is closer to the national average) make them likely locations for future IT growth, although their fortunes seem less tied to the IT cycle than our other urban IT centers.

Overall, our results suggest that the substantial IT presence built up in major urban IT centers during the 1990s survived the IT bust of 2001 and 2002. As IT investment and the IT sector more generally gain momentum, these IT centers likely will regain their prominence. However, the results also suggest that the IT centers leading the way during the last expansion may not be at the top in the next period of development. Those with highly specialized IT sectors may find themselves less able to respond to changes in product demand and development than those with a more diversified IT portfolio.

Appendix

Population and Personal Income per Capita (2000)

Region	Population (millions)	Personal income per capita ($)
Atlanta	4.15	33,507
Austin	1.26	32,185
Boston	6.07	39,125
Dallas	5.26	33,412
Denver	2.60	37,158
Los Angeles	16.44	29,488
Portland	2.27	30,619
S.F. Bay Area	7.06	47,180
Seattle	3.57	36,386
Washington, D.C.	7.64	37,684
U.S. Metro Total	226.81	31,380
United States	282.22	29,760

Source: Authors' tabulations using data from the U.S. Bureau of the Census and BEA.

References

American Electronics Association. 2000. *Cybercities*. Washington, DC.

American Electronics Association. 2003. *Cyberstates 2003*. Washington, DC.

Audretsch, David B., and Maryann P. Feldman. 1996. "R&D Spillovers and the Geography of Innovation and Production." *American Economic Review* 86(3) (June) pp. 630–640.

Beardsell, Mark, and Vernon Henderson. 1999. "Spatial Evolution of the Computer Industry in the USA." *European Economic Review* 43(2) (February) pp. 431–456.

Bessen, James, and Robert M. Hunt. 2003. "An Empirical Look at Software Patents." Manuscript, Federal Reserve Bank of Philadelphia (July).

Ciccone, Antonio, and Robert E. Hall. 1996. "Productivity and the Density of Economic Activity." *American Economic Review* 86(1) (March) pp. 54–70.

Cortright, Joseph, and Heike Mayer. 2001. "High Tech Specialization: A Comparison of High Technology Centers." The Brookings Institution, Center on Urban and Metropolitan Policy, Survey Series (January).

DeVol, Ross C. 1999. "America's High-Tech Economy: Growth, Development, and Risks for Metropolitan Areas." Research report, Milken Institute, Santa Monica, CA.

Doms, Mark. 2004. "The Boom and Bust in IT Investment." *FRBSF Economic Review* 2004.

Drennan, Matthew P. 2002. *The Information Economy and American Cities*. Baltimore: Johns Hopkins University Press.

Duranton, Gilles, and Diego Puga. 2001. "Nursery Cities: Urban Diversity, Process Innovation, and the Life Cycle of Products." *American Economic Review* 91(5) (December) pp. 1,454–1,477.

Ellison, Glenn, and Edward L. Glaeser. 1997. "Geographic Concentration in U.S. Manufacturing Industries: A Dartboard Approach." *Journal of Political Economy* 105(5) (October) pp. 889–927.

Ellison, Glenn, and Edward L. Glaeser. 1999. "The Geographic Concentration of Industry: Does Natural Advantage Explain Agglomeration?" *American Economic Review* 89(2) (May) pp. 311–316.

Feldman, Maryann P., and David B. Audretsch. 1999. "Innovation in Cities: Science-Based Diversity, Specialization and Localized Competition." *European Economic Review* 43(2) (February) pp. 409–429.

Granger, C.W.J. 1969. "Investigating Causal Relations by Econometric Methods and Cross-Spectral Methods." *Econometrica* 37, pp. 424–438.

Hall, B.H., A.B. Jaffe, and M. Tratjenberg. 2001. "The NBER Patent Citation Data File: Lessons, Insights, and Methodological Tools." NBER Working Paper 8498.

Hellman, Thomas, and Manju Puri. 2002. "Venture Capital and the Professionalization of Start-Up Firms: Empirical Evidence." *The Journal of Finance* 57(1) (February) pp. 169–197.

Howell, Thomas R., Brent L. Bartlett, William A. Noellert, and Rachel Howe. 2003. "China's Emerging Semiconductor Industry: The Impact of China's Preferential Value-Added Tax on Current Investment Trends." Report, Dewey Ballantine LLP (for the Semiconductor Industry Association) (October).

Jacobs, Jane. 1969. *The Economy of Cities*. New York: Random House.

Saxenian, AnnaLee. 1994. *Regional Advantage: Culture and Competition in Silicon Valley and Route 128*. Cambridge, MA: Harvard University Press.

Stiroh, Kevin. 2002. "Information Technology and the U.S. Productivity Revival: What Do the Industry Data Say?" *American Economic Review* 92(5) (December) pp. 1,559–1,576.

U.S. Department of Commerce (Economics and Statistics Administration). 2003. "Digital Economy 2003." Report (December).

Valletta, Rob. 2003. "Is Our IT Manufacturing Edge Drifting Overseas?" *FRBSF Economic Letter* 2003–30 (October 10).

Wilson, Daniel. 2003. "Are We Running Out of New Ideas? A Look at Patents and R&D." *FRBSF Economic Letter* 2003–26 (September 12).

The Boom and Bust in Information Technology Investment*

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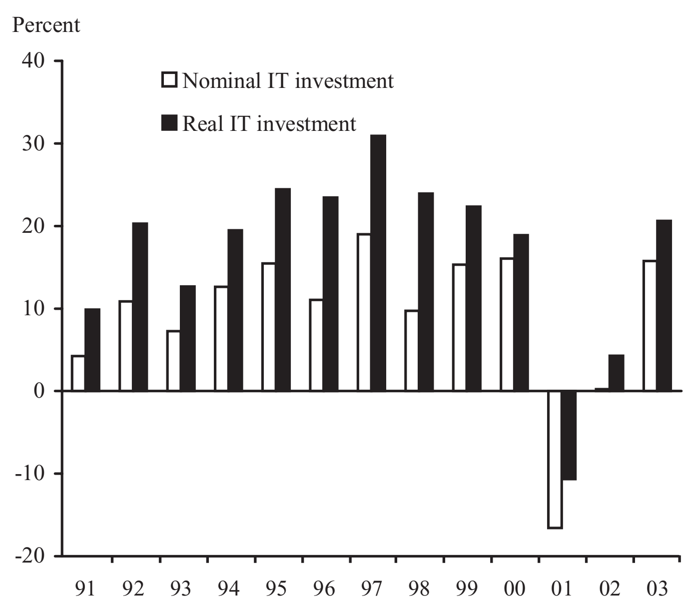
The growth rate of business investment in information technology boomed in the 1990s and 2000 before plunging in 2001. This boom and bust raises some natural questions: what were the reasons for the accentuated swings in growth rates, and, more importantly, what do those reasons portend for the future of IT investment? Much of the increase in IT investment in the late 1990s appears to be attributable to falling prices of IT goods, which in turn is largely attributable to technological change. However, IT investment was much higher in 1999 and 2000 than a model would predict. Another reason for the high growth rates in IT investment was that expectations were too high, especially in two sectors of the economy, telecommunications services and the dot-com sector. Looking ahead, technological change in the IT area will likely continue to move quickly, in large part because large amounts of research and development are being devoted to finding further technological breakthroughs.

1. Introduction

The last recession may well be remembered as a high-tech recession. The growth rate of investment by businesses in computers, communications equipment, and software (referred to as IT investment in this paper) boomed in the 1990s and 2000 before plunging in 2001. As shown in Figure 1, growth in real IT investment was especially strong between 1995 and 2000, averaging 24 percent per year and adding an annual average of over 3/4 percentage point to GDP growth (not shown).[1] However, in 2001, IT investment contracted sharply, with real IT investment falling nearly 11 percent and nominal investment plunging almost 17 percent.[2] In 2002, with a recovery in IT investment late in the year, real and nominal IT investment were up modestly. IT investment picked up further in 2003, with real investment posting a respectable 21 percent increase.[3]

The boom and bust in IT investment raises some natural questions: what were the reasons for the accentuated swings in growth rates, and, more importantly, what do those reasons portend for the future of IT investment? For example, were the very high growth rates in IT investment followed by a contraction the result of a surge in technological change in the late 1990s, or overly optimistic

Figure 1
Annual Percent Change in IT Investment



Source: Bureau of Economic Analysis. Percent changes based on year-end values.

*I thank Fred Furlong and Anita Todd for their comments. I also thank Ashley Maurier for technical assistance and Ana Aizcorbe, Charles Gilbert, and Michael Kiley for data.

1. All percent changes are reported on an end-of-year basis unless otherwise noted.

2. When it comes to IT investment, the distinction between nominal and real investment can be quite important; for a discussion of the relationship between nominal and real investment and prices, see Box 1.

3. For a fuller and very readable discussion of the importance of IT to the economy, see Department of Commerce (2003).

Box 1
The Relationship between Prices and Nominal and Real Investment

Large differences in the growth rates for nominal investment and real investment can arise because the prices for high tech goods fall much more quickly than overall prices. As an example, say that nominal investment in (that is, actual dollars spent on) computers falls 10 percent in a year. However, as has been well documented and extensively studied, the prices of computers tend to fall sharply, averaging over 20 percent per year. In our example, suppose that prices fall 20 percent. Then, although nominal investment falls 10 percent, real investment grows by 12.5 percent.[1] Therefore, there can sometimes be confusion over what constitutes a rebound in investment.

1. The real growth rate in percent between two time periods (t and $t+1$) is $100 \times [(N_{t+1}/P_{t+1})/(N_t/P_t) - 1]$, where N denotes nominal investment and P is the price index.

expectations on the returns to IT investment, or changes in the service lives of IT goods, or some other factors?

To get at the answers to these questions, I present results from a model of IT investment to identify those portions of investment that are "explained" by economic fundamentals and those portions that are "unexplained." I then discuss and examine the reasons for the explained and unexplained portions. In a nutshell, the model suggests that most, but not all, of the very high rate of IT investment growth from 1994 through 1999 can be explained. The driving force behind the high rates predicted by the model is the cost of IT goods; these costs fall much more quickly than costs for other investment goods, hence the demand for IT goods rises. However, the gap between actual and predicted IT investment (the unexplained portion) grows in 1999 and 2000. Additionally, IT investment falls more quickly than the model predicts in 2001 and stays below the model's predictions for 2002 and into 2003 (that is, the unexplained portion turns negative and remains negative).

In trying to understand what can "explain" the unexplained portions, one hypothesis that I examine is that overly exuberant expectations about IT investment led businesses to overinvest in IT systematically. At first glance, the sharp contraction in IT investment following several years of exceptionally high growth lends credence to this hypothesis. However, the exceptional productivity performance in the economy that coincided with the boom in IT investment throws this hypothesis into doubt. With that said, there were indeed pockets in the economy that, ex post, overinvested in IT; two such pockets were the telecommunications services and dot-com sectors. Capital spending by telecom service providers, which are large consumers of IT products, surged in 2000 and subsequently fell sharply in 2001 and 2002. In fact, estimates show that the large swing in nominal IT investment between 2000 and 2001 was greatly exacerbated by the telecom service industry, and that the telecom service industry placed a significant drag on nominal IT investment in 2002. Data for the dot-com industry are harder to come by. However, by several measures, it appears that the rise and fall of the dot-com industry plays a nontrivial role in understanding the "unexplained" portion of IT investment.

Another hypothesis for why the model of investment would have underpredicted then overpredicted IT investment is that service lives of IT equipment were shortened in the late 1990s (boosting investment) and subsequently lengthened in this decade (damping investment). One reason why service lives were shortened in the late 1990s was because concerns surrounding the effects of the century date change (known as Y2K) forced firms to replace some of their IT capital earlier than they had expected. However, based on survey data, I find that the Y2K problem played a minor role, at best, in the swings in IT investment. A second reason for shortened service lives is that advances in personal computer (PC) software increased the obsolescence of PCs; thus, many firms upgraded their PC stock in the late 1990s, earlier than they had anticipated. So far this decade, so the story goes, the rate of obsolescence has apparently been reduced, lengthening the service lives of PCs and damping IT investment. Quantifying this story is extremely difficult, but there is much circumstantial evidence suggesting that this may indeed have happened.

The stories just discussed help explain why IT investment was so high in 1999 and 2000 and why it fell so quickly in 2001. However, the most salient feature of the model of IT investment is just how much growth in IT investment it predicted. The growth in predicted IT investment stems largely from the fall in prices of IT goods, which results largely from technological progress. I find that prices for several IT goods fell very quickly during the late 1990s, and that these drops in prices appear to coincide with an acceleration in technological progress. Prices in the late 1990s probably fell even faster than the official data indicate, especially for communications gear and software. There is also some evidence that technological progress eased up some at the beginning of this decade but continues to gain at a rapid pace. Looking forward, it appears that the pace of technological change for IT products should continue for a while, reflecting the large amounts that companies are spending on R&D and the expectations about what products can be developed.

In this paper, Section 2 presents the stylized facts about investment in IT goods. Section 3 discusses a model of IT investment, highlighting those factors that are important behind investment and a rough framework to think about IT investment. To address some possible reasons for the errors in the investment model, I present a discussion of the role of overly optimistic expectations in Section 4 and the role of shortened IT service lives in Section 5. To explain one of the more important determinants of IT investment, I describe what has happened to prices and technological change for computers, communications equipment, and software in Section 6. Section 7 concludes with some information about what may be in store for technological change in the IT field.

2. Basic Facts of the Boom and Bust

Investment in IT has become an increasingly important component of the economy and played a disproportionately large role in the past economic downturn. In 1990, nominal investment in IT goods totaled just $131.5 billion, a bit less than one-third of private nonresidential equipment and software (E&S) investment. By 2000, IT investment had surged to $401.6 billion, close to a 44 percent share of E&S spending. Nominal IT investment still accounted for close to 43 percent of E&S investment in 2003, two years after the IT bubble burst.

These IT investments contributed significantly to GDP growth during the late 1990s and contributed greatly to the swings in GDP growth during the past economic downturn. For instance, IT investment contributed about 3/4 percentage point to real GDP growth in 1998, 1999, and again in 2000. However, in 2001, the drop in IT investment subtracted 0.4 percentage point from GDP growth. After having a minor effect in 2002, IT investment once again provided a substantive boost to GDP in 2003 by contributing 0.7 percentage point to growth.

Table 1 presents a fuller description of what happened to IT investment in the late 1990s and so far this decade. The table summarizes the changes in nominal investment, prices, and real investment for three IT categories: software, computers, and communications equipment. The table also presents statistics on nonresidential investment outside of IT (non-IT). There are several stories to take away from the table. The most striking is that nominal and real investment grew very sharply during the late 1990s and into 2000 for all IT categories. Between 1995 and 2000, growth in IT investment in real terms averaged nearly 24 percent per year, five times greater than investment in other types of equipment. In nominal terms,

Table 1
Changes in Nominal Investment, Real Investment, and Prices for IT

	Average annual percent change			Percent change from preceding year				
	1990–1995	1995–2000	2000–2003	1999	2000	2001	2002	2003
Nominal investment								
IT	10.0	14.2	–1.2	15.3	16.0	–16.6	0.2	15.5
Software	9.5	18.5	0.8	24.1	12.2	–9.6	2.5	10.6
Computers	13.5	7.1	1.4	6.6	9.2	–23.4	8.4	25.4
Communications equipment	7.2	15.5	–6.4	11.0	28.6	–21.1	–9.8	15.2
Non-IT	6.8	4.9	–1.4	3.6	0.2	–7.8	0.3	3.6
Prices								
IT	–6.2	–7.8	–4.8	–5.7	–2.4	–6.6	–3.9	–4.0
Software	–2.7	–0.5	–0.9	2.3	3.5	–0.4	–0.7	–1.7
Computers	–14.8	–21.0	–14.3	–18.3	–11.1	–20.6	–11.8	–10.1
Communications equipment	–1.4	–3.4	–2.7	–4.7	–3.2	–3.9	–2.4	–1.8
Non-IT	1.9	0.4	1.3	–0.1	0.5	0.6	0.6	2.8
Real Investment								
IT	17.2	23.8	3.9	22.3	18.9	–10.7	4.3	20.3
Software	12.6	19.1	1.8	21.3	8.4	–9.3	3.2	12.6
Computers	33.2	35.6	18.3	30.5	22.9	–3.5	22.9	39.6
Communications equipment	8.7	19.6	–3.8	16.6	32.9	–17.9	–7.6	17.4
Non-IT	4.8	4.4	–2.7	3.7	–0.3	–8.3	–0.3	0.8

Source: Bureau of Economic Analysis. All figures computed using year-end values.

growth in IT investment in the late 1990s was nearly three times as great as in other equipment.

The gaps between the growth rates in real and nominal IT investment reflect the estimated changes in prices for IT equipment and software based on price deflators compiled by the Bureau of Labor Statistics (BLS) and the Bureau of Economic Analysis (BEA). These agencies face a difficult task in deriving accurate price indexes for IT products because IT products are constantly changing. There has been much research into measuring prices for computers (the component of IT that shows the fastest price declines), but much less progress has been made in measuring quality-adjusted prices for software and communications equipment. As I discuss in Section 6, it is very likely that prices for these two components actually fell much faster than the official data indicate, implying that the growth in real investment was even higher than reported in the table.

Another notable feature in Table 1 is the sharp reversal of fortune that befell IT investment and other investment to a lesser extent in 2001. To paraphrase, the higher the rise, the harder the fall. Nominal IT investment dropped almost 17 percent in 2001, a whopping 33 percentage point reversal, reflecting declines in all three IT categories, but especially for computers and communications equipment. Real investment in IT declined 10.7 percent in 2001, representing an equally stunning swing in growth rates. The slide in IT investment began to reverse slowly in 2002 and had recovered substantially by the end of 2003.

Although business demand for IT goods declined sharply during the recession, the declines should not be overstated since the level of investment remained high. For instance, nominal investment in 2002 was at the same level as it was in 1999, and real investment was 30 percent higher, indicating that businesses continued to add to their stock of IT hardware and software, at least in real terms.

3. A Model of IT Investment

The data in the previous section show IT investment went through a period of phenomenal growth followed by a sudden contraction. This brings to mind the question, how much of this pattern was based on economic fundamentals and how much was based on other factors? Another way to pose the question is to ask, how much of the boom and bust in IT investment can be "explained" by traditional models of IT investment and how much is "unexplained"?

One model of IT investment, as described in Kiley (2001), is part of the larger macroeconomic model, known as FRB/US, that is maintained at the Board of Governors of the Federal Reserve System. At its heart, the FRB/US model asks what profit-maximizing amount of IT capital firms in the U.S. economy should have, what it refers to as the "optimal" IT capital stock. The optimal IT capital stock for the economy depends on a number of factors, including a concept referred to as the "user cost of capital." The user cost of capital is akin to the wage rate for labor in that it attempts to capture how much it costs a firm to use a piece of capital over a period of time, just as the wage rate attempts to capture how much a firm has to pay for a worker. Box 2 provides more details. Although the exact construction of the user cost of capital can be a little convoluted, it stands to reason that if, for instance, the user cost of IT declines, then firms would buy more IT and substitute away from other factors of production, such as labor or other types of capital.

Figure 2 shows indexes of the user cost for IT goods and for other investment goods since 1990.[4] The user cost of IT goods has fallen over time, averaging about 6 percent per year in the early 1990s and over 7 percent in the late 1990s. In contrast, the user cost of non-IT goods increased an average of little more than 1 percent per year from 1990 to 2003. Over the 1990s, the primary factor driving down the user cost of IT was the decline in the price of IT capital goods, at least as measured by the BLS and BEA. The decline in the prices for IT goods was stunning, and, like other normal goods, these falling prices pushed up the quantity of IT capital demanded by busi-

Box 2
The User Cost of Capital

The user cost of capital is made up of two types of costs. The first is the cost of the acquisition of the capital good, and this equals the prevailing interest rate, i, multiplied by the purchase price of the capital good, p_t.

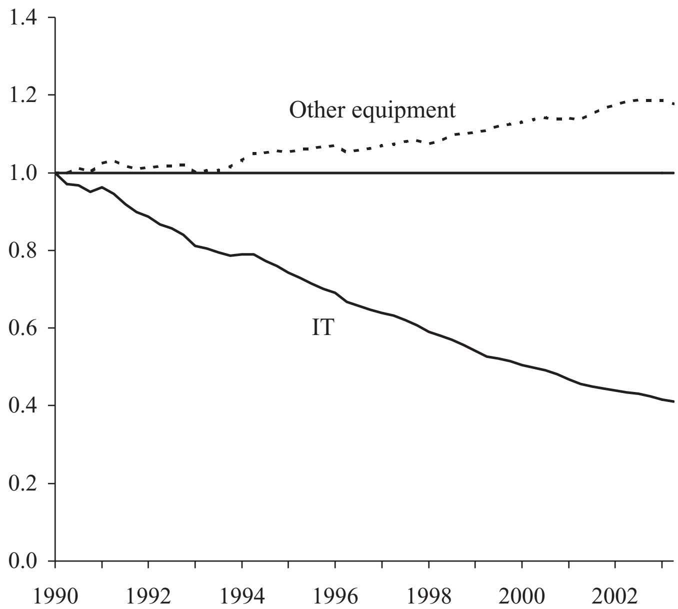
The second type of cost is what happens to the value of the capital good over the period it is used. This type of cost includes the change in prices, π, and depreciation, δ. Depreciation is the idea that the value of the good declines over time simply because it ages. The change in prices, π, enters into the user cost because the worth of a good depends on the market for that good. Say, for example, a company buys a computer for $1,000. If computer prices fall 20 percent in the next year, that computer will have lost $200 in value because of price changes alone.

Putting all of these components together (excluding the effects of taxes for simplicity), the user cost of capital can be written as

$$(1)\quad UC_t = p_t(i_t + \delta - \pi_t).$$

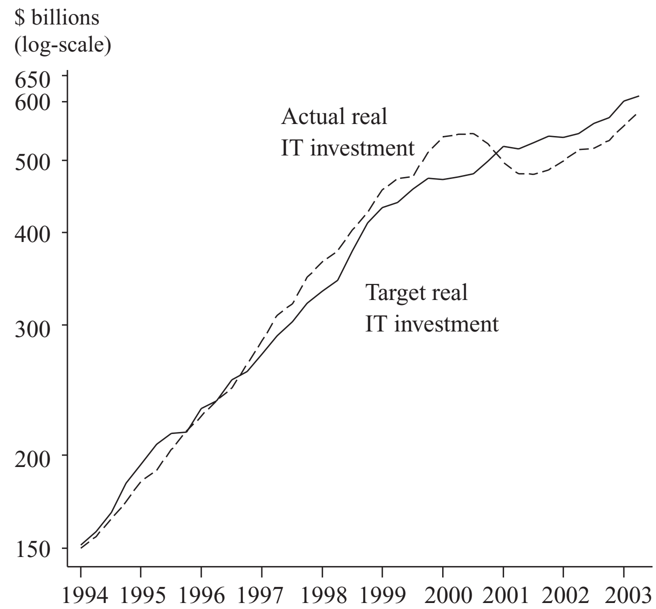
4. The user costs shown here do not make any adjustments for taxes.

FIGURE 2
INDEXES OF USER COSTS FOR IT AND OTHER EQUIPMENT
(1990:Q1=1)



Source: Federal Reserve Board of Governors.

FIGURE 3
ACTUAL AND TARGET REAL IT INVESTMENT
(1996 $ BILLIONS)



Source: Federal Reserve Board of Governors.

nesses. In fact, the declining user cost for IT is the primary driver of the strong IT investment during the 1990s, according to FRB/US.

Using the user cost of capital, FRB/US estimates how much IT investment would be necessary to reach the optimal capital stock. This is referred to as the "target level" of investment. Figure 3 shows actual real IT investment and the target level of real investment predicted by FRB/US since 1994.[5,6] The figure shows that the target level of investment and actual investment track each other fairly well from 1994 to 1998, though FRB/US tends to systematically underestimate IT investment a bit. For instance, over the 1994 to 1998 period, the average target IT investment growth is 24.4 percent per year, compared to 25.2 percent for actual IT investment. The underestimation of the model is about $26 billion (in 1996 dollars) as of 1998. That is, IT investment was about 6 percent greater in 1998 than would be expected based on the model.

The model does not do quite as well predicting the rapid growth of IT investment in 1999 nor the slump during the recession and the degree of rebound. For instance, the model predicted that real investment would increase 14.7 percent in 1999, when in fact it increased 20.5 percent. Also, in 2001, the model predicted a 7.9 percent increase, but investment actually fell 7.8 percent.[7] In 2002, actual investment remained below predicted investment. In the first half of 2003, some shortfall in actual investment still was evident, but it was quite small.

The results in Figure 3 appear to take a good deal of the mystery out of the boom in IT investment by businesses. A concern is that the results in Figure 3 are based on an estimated model. However, the results of the model should not be taken as truth for several reasons. For example, the outputs of the model are only as good as the inputs, and, as I discuss later in this paper, it is extremely difficult to measure the components of IT properly. Additionally, there are the problems associated with any estimated model, such as parameters that may vary over

5. The FRB/US estimates are based on data from before the benchmark revision in December 2003. It is too early to tell if the new data will produce a better or worse fit. However, the percentage decrease in real IT investment in 2001 before the benchmark revision was 7.2 percent, and after the benchmark revision the drop was 2.7 percent.

6. Figure 3 is drawn with a logarithmic vertical scale instead of a traditional linear vertical scale. A straight line on a graph with a logarithmic vertical scale indicates that a series is changing at a constant rate. In contrast, when graphed with a traditional linear vertical scale, that same series that increases at a positive constant rate would become steeper over time. The distinction between linear and logarithmic scales can be especially important for a variety of series in the IT industry that are characterized by high growth rates, such as Moore's law, the speed of microprocessors, the prices of IT goods, and so on.

7. These gaps are large relative to how FRB/US performs for other types of equipment investment.

time or missing factors in the equations. Therefore, it is still interesting to ask whether there is any other evidence of overinvestment in IT during the 1990s.

Another more indirect way to examine the IT investment trend is to assume that firms are making the correct decisions in terms of how much they are investing in IT, and then examine what has happened to productivity. The logic behind this approach is that, if there were a great deal of overinvestment in IT—that is, if a lot of IT goods were purchased that ended up not being very useful—then productivity would not be as high as expected. This is not a conclusive test, as there are many factors that affect productivity, but, as discussed in Box 3, it appears to be increasingly difficult to tell a story that there was too much investment in IT given what has happened to productivity growth and given the multitude of stories that cite the importance of IT. With that said, however, there were several sectors that obviously overspent on IT (and on other equipment, for that matter), and they are described in the next section.

4. Ebullience

Perhaps the story that is first and foremost in many people's minds to explain the excessive IT investment in 1999 and 2000 is that expectations about the rate of return on IT investment were too high. In the late 1990s, the dot-com industry was growing and there was a sense that the way business was conducted around the world was changing, creating a "new economy." Businesses believed that they had to invest heavily in IT if they wanted to be part of this new economy. Using the language from the model section, businesses thought that there was an outward shift on the returns to IT investment, increasing the desired capital stock and, therefore, increasing investment in IT goods. In 2000 and 2001, expectations began to sour (lowering the expected rate of return on IT goods) and the reverse happened: firms cut investment in IT goods.

Although this story has a tremendous amount of intuitive appeal, the question is, to what extent did changes in

Box 3
The Relationship between Productivity Growth and IT Investment

Labor productivity grew at an average rate of 1.4 percent between 1973 and 1995. Since 1995 through the end of 2003, labor productivity growth perked up to 3.1 percent, with especially strong gains of over 4 percent since the end of 2000.

Why did productivity growth pick up in the late 1990s and so far this decade? To answer that question, many studies have decomposed labor productivity growth into several sources.[1] These sources include improvements in the quality of labor, increases in the amount of capital, and improved efficiencies in producing with a given amount of capital and labor. This last form of productivity improvement is often called total factor productivity, or TFP. Although different studies use different decompositions, most come to the conclusion that a good deal of the pickup in labor productivity growth comes from a pickup in TFP.[2]

If firms made many unwise capital investments, including IT investments, all else equal, then TFP would be adversely affected. Yet, TFP has gone up during and after the strong surge in IT spending. Now, there are many reasons why TFP may have gone up, and TFP is something that is not well understood (in fact, TFP is sometimes referred to as a measure of our ignorance). However, the collected stories about the improving productivity performance of the U.S. economy resonate an IT theme, either directly or indirectly. For instance, Jorgenson, Ho, and Stiroh (2002) find that industries that were intense users of IT accounted for a disproportionate share of productivity growth. Similar results are produced independently by the Department of Commerce (2003). For instance, the finance and retail industries posted above average gains in productivity growth and they are also sectors that are also relatively IT-intensive.

Digging beneath the surface a bit, the McKinsey Global Institute has come out with several studies (McKinsey 2001, 2002) that examine productivity growth and ask, sometimes specifically, what role IT played. A theme of the McKinsey studies is that IT was one reason, but not the only reason, for the surge in productivity growth. Other reasons McKinsey cites include increases in competition (in the case of the development of microprocessors) and changes in the regulatory environment (in the case of cellular phones). Another theme in the McKinsey studies is that investment in IT does not in itself yield marked productivity improvements. Instead, organizations must make complementary changes in the way they do business to reap the full rewards that IT potentially offers. In a related vein, Basu, et al. (2003) argue that IT is a general purpose technology, that is, a technology that is widely used in a number of different applications. As such, it takes time for firms and industries to learn how to use IT, so the improvements we are seeing more recently in TFP are the fruits of investments made several years ago.

1. Several of the more commonly cited studies include Oliner and Sichel (2002), Gordon (2003), Jorgenson, Ho, and Stiroh (2002), and the Council of Economic Advisors (2003).

2. It should be noted that most of the pickup in TFP is outside of the IT-producing industries.

expectations affect the swing in IT goods? It is dangerous to point to examples and then make generalizations, because regardless of the type of investment good we could examine—computers, airplanes, aluminum smelters—one can always find examples of investments that turned out not to be wise. The more appropriate question to ask is, what happened on average or, if there were particular pockets of excessive enthusiasm, how large were those pockets and what effects could they have had on the aggregate figures for IT investment? What follows, then, is a closer examination of two industries that epitomized overinvestment in IT.

4.1. Dot-com Overinvestment

There were expectations that new firms that relied heavily on the Internet, and firms that provided services to other businesses that relied heavily on the Internet, would be wildly profitable, a claim that only a few firms would be able to make several years later. Ebay is one such dot-com company that has survived, while Pets.com and Furniture.com are examples of dot-com companies that failed. Unfortunately, there are no accurate statistics on the dot-com industry, especially when it comes to IT capital spending. However, there are several ways to obtain some back-of-the-envelope calculations to see how potentially important these companies may have been to the swings in IT investment. One method is to examine patterns of venture capital (VC) spending and another is to examine employment in industries that have properties similar to dot-coms. Both methods come to a similar conclusion: the dot-com bubble and its bursting could have accounted for a small portion of the excessive run-up in IT investment and a somewhat larger portion of the decline.

The first method of measuring the potential magnitude of dot-coms on the investment swings is to examine VC spending. According to the MoneyTree survey,[8] VC spending (excluding health care and biotechnology) surged in 2000 to nearly $98 billion, a staggering increase from nearly $18 billion just two years earlier. The question is, how much of this money was spent on IT? According to data from Informationweek,[9] companies tend to spend very little of their revenue on IT. For instance, even telecom firms (which are IT-intensive) are estimated to spend only about 4 percent of their revenue on IT, and about one-third of that spending is on salaries. If we assume that companies that received VC funding spent 5 percent of their funding on IT equipment and software (about double the rate of telecom companies), then VC spending accounted for $2.4 billion of the $53.8 billion increase (4.5 percent) in IT spending between 1999 and 2000. However, between 2000 and 2002, the drop in VC spending would have accounted for a $4.1 billion drop in IT spending, about 7.5 percent of the $55 billion decline.

Another approach to looking at the effect dot-coms had on IT investment is to examine employment in industries that are dot-com-like. Four industries that likely encompassed many of the dot-coms are wholesale electronic markets and agents and brokers; electronic shopping and mail-order services; Internet service providers and web search portals; and data processing, hosting, and related services. Between 1995 and the end of 2000, employment in these industries accounted for 2.3 percent of all net nonfarm jobs created in the U.S. (365,000 compared to 16.1 million created elsewhere in the nonfarm sector). In terms of the downturn though, these industries accounted for about 5 percent of the decline in total nonfarm employment.

In terms of the role that these industries played in the swings of IT investment, we need to make an assumption about how IT-intensive they are relative to the rest of the economy. For example, let's suppose these industries invest three times more in IT per employee than other industries do.[10] Under this assumption, these industries would have accounted for about 6.5 percent of the increase in IT spending from 1995 to 2000 and 13.1 percent of the drop from 2000 to 2002.

4.2. Telecommunications Service Industry Overinvestment

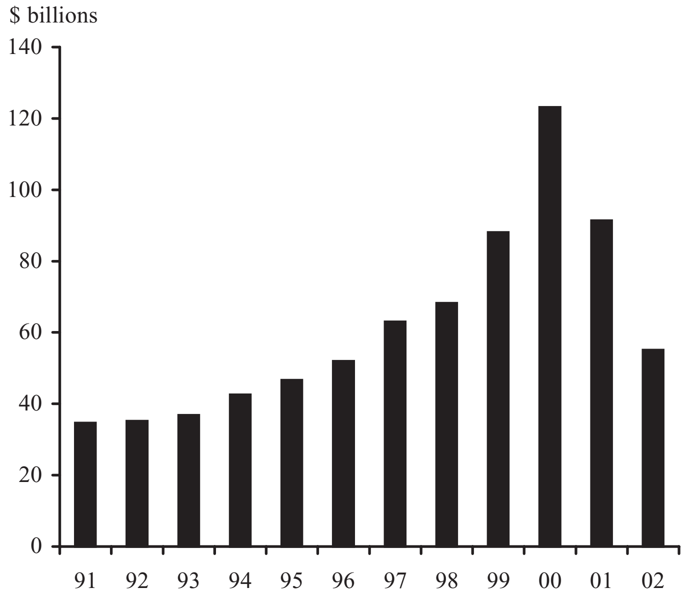
More than any other sector, the telecom service industry was the poster child of overinvestment. Spurred on by the Telecommunications Act of 1996 and ebullient expectations for future demand, the telecom service sector went on a capital expenditure binge. As shown in Figure 4, capital investment by publicly traded telecom service companies rose sharply in the late 1990s, starting at $47 billion in 1995 and peaking at $121 billion in 2000. Since then, however, the telecom service industry landscape is littered with the wrecks of overly optimistic expectations, as witnessed by the bankruptcies by WorldCom, Global Crossing, and numerous smaller

8. The MoneyTree Survey is a collaboration among PricewaterhouseCoopers, Thomson Venture Economics, and the National Venture Capital Association.

9. See www.Informationweek.com.

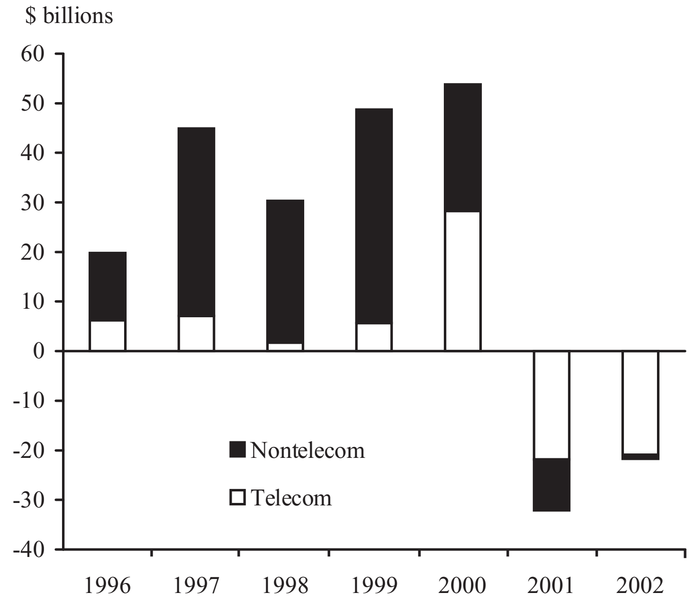
10. Based on the 1998 Annual Capital Expenditure Survey (ACES), this assumption would make dot-coms about two times more IT-intensive than the financial services industries.

Figure 4
Capital Spending by Publicly Traded Telecommunications Service Providers



Source: Compustat and author's calculations.

Figure 5
Changes in Estimated Nominal IT Spending by Telecom and Nontelecom Companies ($ Billions)



Note: All figures are year-over-year changes
Source: Author's calculations based on data from Compustat, the Annual Capital Expenditures Survey (multiple years), and the 1997 Capital Flows Tables (from BEA).

firms. By 2002, investment had fallen by over half to $49 billion.[11,12] These large swings in investment by this single industry likely helps explain a portion of the swing in IT investment, since telecom service providers are big spenders on IT equipment.

Working on the assumption that capital spending by telecom service providers fell by 20 percent in 2001 and using information from the U.S. Census Bureau's 1998 Annual Capital Expenditures Survey and the BEA's 1997 Capital Flows Table, Figure 5 shows the changes in estimated annual IT spending by telecom and nontelecom firms.[13] In 2000, telecom companies went on a spending binge, accounting for a majority of the increase in IT investment in the country. Almost as pronounced as the 2000 increase is the 2001 decrease. I estimate that IT spending by telecom companies dropped by $22 billion, more than two-thirds of the total decrease in IT spending. In 2002, I estimate that a further drop in telecom spending accounted for nearly all of the decline in total IT spending.[14] The Appendix provides a more detailed look at the causes of the boom and bust in capital investment by the telecom service industry.

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11. The data for publicly traded companies are very close to the figures reported in ACES for communications service firms. For instance, government data show that telecom companies ramped up capital spending by 206 percent between 1994 and 2000, slightly above the 189 percent increase for the publicly traded companies. U.S. Census Bureau data are usually about 90 percent of the publicly traded company data, again likely reflecting that some firms in our sample do make capital investments outside of the U.S. The one anomaly between the two series occurs in 2001, the last year government data are available, when the government data show only a 7 percent drop in capital spending, whereas publicly traded companies register a 25 percent drop. Given what happened in the industry, the numerous reports of companies slashing capital spending, various financial indicators of the industry, what happened to revenues of companies that make communications gear, and the number of bankruptcies, the true drop in investment spending could be much larger than the figures reported by the Census Bureau.

12. Based on results from the first half of 2003, it is likely that capital spending for these companies increased in 2003 to over $55 billion.

13. According to the 1998 ACES, the communications industry spent 72 percent of its capital expenditures on information processing equipment. Additionally, the 1997 Capital Flows Table suggests that, of capital equipment spending by communications firms, 62 percent is doled out on communications equipment, 9 percent on computers, and 12 percent on software.

14. The decompositions presented in Figure 5 are based on several assumptions, so they should not be taken literally. Nonetheless, the results that telecom service firms would have accounted for a disproportionate share in the 2000/2001 swing in IT investment is robust to a wide range of alternative assumptions.

5. Changes in IT Service Lives

Most investment models assume depreciation is constant over time, that is, that capital goods are discarded according to a fixed schedule. These assumptions about fixed retirement schedules are made because there is a lack of information otherwise.[15] For IT goods, there were three events in the 1990s and 2000 that would have caused firms to shorten the service lives of their IT goods unexpectedly and then boost their IT investment. The first was the famous Y2K problem, which implied that some software and hardware would not function or would function improperly after December 31, 1999. As a result, firms had to replace some hardware and software sooner than they had expected. Second, unexpectedly large advances in software requirements during the second half of the 1990s induced firms to upgrade their computer hardware more quickly. Finally, a more nuanced argument has been put forth by Whelan (2000) that says that service lives are shortened when prices fall rapidly; during the late 1990s, computer prices fell extremely rapidly and arguably more rapidly than firms expected.[16] The three stories have a certain amount of credibility. What is unfortunate, though, is that it is difficult to quantify the importance of the two latter stories.

5.1. Preparations for Y2K

According to the Department of Commerce (1999), it is estimated that about $100 billion was spent on "fixing" the Y2K problem from 1995–2001.[17] Money was spent on fixing and testing software, replacing embedded chips that had the Y2K problem hard-wired, and replacing computers and software earlier than they would have been otherwise. Based on data in the Department of Commerce report, it is unlikely that fixing the Y2K problem had an appreciable effect on the time series pattern of aggregate IT spending.[18] For instance, in 1998, the year in which Y2K-related expenditures peaked, these expenses accounted for only an estimated $4.8 billion in software (compared to a total $140 billion that private businesses spent on software in that year) and $3.2 billion in hardware (compared to a total $165 billion that private businesses spent on IT hardware).[19]

5.2. Changes in PC Hardware Requirements

Perhaps more important in understanding the swings in IT investment than Y2K are the more general relationships between hardware and software, especially for PCs. During the 1990s, sales of PCs outstripped sales of midrange and mainframe computers, and PCs became a more important component of the IT capital stock. Also during this decade, there were tremendous changes in the technology of PCs and in their software. Windows-based operating systems and software became the norm, as did the ability to browse the Internet. In the face of these software changes, the replacement cycle of PCs may have changed. Some research suggests that the mean service life of personal computers shortened during the late 1990s (McKinsey 2001), which provided a boost to investment. During the more recent downturn, there were claims that the average service lives of PCs were lengthened, damping investment. However, just how long PCs (or other IT goods for that matter) are used before they are retired is not known; in most investment models and in calculations that estimate the contribution of IT capital to productivity growth, the replacement cycle is considered to be constant.[20]

The story is that during the late 1990s there was a surge in the hardware requirements needed for running various software programs. Since the recommended configurations for many computer operating systems are very similar to the recommended configuration for the latest version of Microsoft Office, I use that software package's configurations to measure changes in business requirements for computing. The increases for minimum required hardware during the mid- to late 1990s are stark: between 1994 and 2000, RAM requirements increased at a 67 percent annual rate (from 2 megabytes to 64 megabytes), while hard disk requirement increased at a 90 percent annual rate (from 8 megabytes to 650 megabytes). Therefore, firms may have replaced their PCs more frequently during the late 1990s and less since then.

5.3. Faster Falling Prices, Faster Replacement

The other story of how service lives may vary over time is provided by Whelan (2000) who suggests that the faster the

15. Just how little is known about service lives is discussed in Doms, et al. (2003).

16. Another form of increased depreciation that may have been important during the 1990s was the depreciation of midrange and mainframe computers induced by the widening acceptance of the personal computer.

17. The Department of Commerce analysis uses estimates from the Federal Reserve and from IDC.

18. According to IDC, about 16.5 percent of these Y2K expenditures were on software and 10.9 percent were on hardware.

19. Another way the Y2K problem may have affected IT investment is that investment in the latter part of 1999 could have been postponed until 2000, until after the effects of Y2K were established. The magnitude of this swing is hard to quantify and is not likely to be large.

20. In calculating depreciation rates for capital stocks, there are several components, including the loss of value as a good ages and when a good is retired. For computers, it is the latter that is the most important, as shown by Doms et al. (2003).

Box 4
The Relationship between Technological Change and Prices

Although measuring the changes in the technology of goods (such as chip speed and horsepower) is interesting in its own right, perhaps a more important question to ask is, how much is our welfare improved by those technological changes? For instance, if Intel comes out with a new microprocessor that is twice as fast as the previous generation, or if General Motors comes out with a car that has twice the horsepower of last year's model, does that mean that we are twice as well-off? Probably not, especially if the faster computers and faster cars are more expensive than the older models.

One way to measure how much our society values technological change is by examining prices. Price indexes are supposed to answer the question of how much money we need today to be as well-off as we were, say, last year. For the economy as a whole, prices tend to increase, so we tend to need more money today than we did last year to maintain a given level of satisfaction. In contrast, prices for high-tech goods tend to fall, implying that not as much money is needed today to spend on IT goods to get the same level of performance that we got last year. In practice though, official price indexes for many high-tech goods likely understate price declines, that is, they understate how much better-off we are because of new and better products.

There are many other factors beyond technological change that affect prices as well, especially in the short-run, such as changes in profit margins, costs of supplies, and production efficiency. However, technological change appears to be the dominant force in the downward price trends for a wide variety of high-tech goods.

pace of price declines, the faster machines will be replaced. As I noted in Section 2, computer prices fell exceptionally quickly in the late 1990s. The thinking behind Whelan's research is that firms incur expenses in maintaining computers, an idea that has a lot of appeal based on estimates of support costs relative to the cost of computer hardware. Facing these costs, when new computer prices drop significantly, firms will be more inclined to buy a newer machine rather than incur the costs of maintaining an older one. The Whelan story reinforces the story that service lives may have decreased in the late 1990s (when computer prices fell the quickest) but have since increased.[21]

6. Technological Change and Prices

One of the driving factors in IT investment has been the rapid drop in the user cost of capital for IT goods, which is driven mainly by the drops in prices for IT goods. Going one step further, the drops in prices for IT are largely driven by technological change, as discussed in Box 4. Given the importance of prices and technological change, this section goes into more detail about what happened to prices and technology for the three components of IT investment.

In particular, one reason for going through this exercise is to try to understand better why prices for IT goods fell very quickly in the late 1990s, more quickly than they had earlier in the 1990s.[22] Did these rapid price declines in the late 1990s coincide with an increased pace of technological change, or did prices appear to fall for other reasons? Also, what has happened to the pace of technological change since then? The answer to the first question appears to be that the pace of technological change did pick up in the late 1990s, at least for certain types of IT products, helping to propel prices downward very quickly. The answer to the second question is less clear. Official prices for IT goods show some deceleration, and there are some areas where technological change may have slowed. However, the deceleration in IT prices is somewhat puzzling given that demand slowed (which usually puts downward pressure on prices) and prices for several types of semiconductors (important components of IT goods) continued to fall very quickly.

6.1. Computers

Given the importance of the prices of IT goods in understanding investment, it is not surprising that there has been some effort exerted in measuring prices for IT goods, much of it devoted to measuring prices for computers. According to the BEA, prices for computers and peripheral equipment fell at unusually high rates in the late 1990s, dropping an average of 21.0 percent per year

21. One way to think about the Whelan story through the user cost of capital framework presented in Box 2 is that the depreciation term is a function of the change-in-price term.

22. This quickening in the fall of prices likely had little effect on the predictions of the FRB/US model though, since IT investment responds slowly to price changes. Kiley (2001) performs a simulation where he holds prices of IT goods fixed at their 1995 level. This simulation shows that it takes several years for the change in the price path of IT goods to manifest itself in significantly lower IT investment.

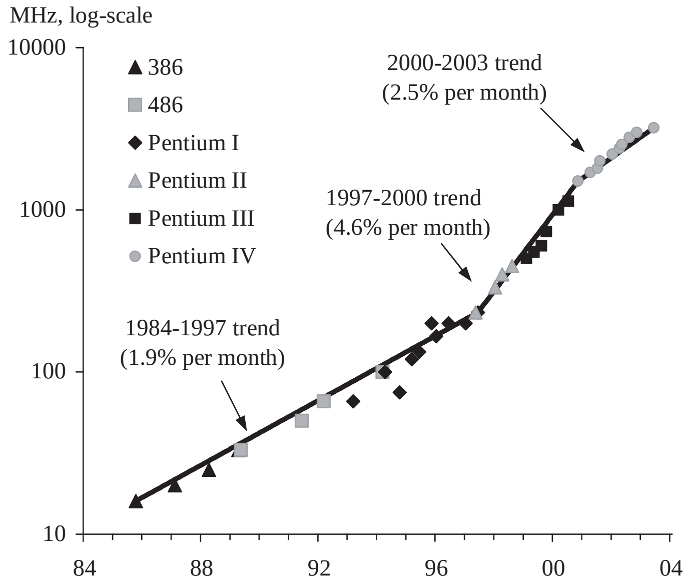
between 1995 and 2000 compared to 14.8 percent for the previous five years. Since 2000, computer prices have fallen at a more modest pace of 14.3 percent.

One approach to understanding computer prices is to examine the prices for the components that make up computers. Two of the more important components are rigid hard drives and semiconductors. Aizcorbe, Flamm, and Khurshid (2002) (hereafter referred to as AFK) conclude that much of the acceleration in the decline of computer prices in the late 1990s can be explained by what happened to the prices of semiconductors.[23] For instance, AFK show that prices for chips that are used in computers fell an average of 13.3 percent between 1992 and 1995, and fell an average of 47.3 percent between 1995 and 1999, reflecting sharp drops in the prices of microprocessors (MPUs) and memory chips.[24] Unfortunately, the data used in the AFK study stop in 1999.

There has been some research exploring why the declines in the prices for semiconductors picked up steam in the latter part of the 1990s. One explanation is that technological change accelerated in the late 1990s, which helped speed up price declines. To address this hypothesis, the International Technology Roadmap for Semiconductors (ITRS) (various issues during the 1990s and 2000s) has noted that the shrinking of the size of features on MPUs and dynamic random access memory (DRAM) chips did accelerate in the second half of the 1990s.[25] To use the terminology of the ITRS, the "technology node cycle," a rough measure for the length of time between the shrinking of features by 50 percent, shifted from three years to two years in the late 1990s and remained at two years through 2003.[26] The smaller the size of the features, the more chips can be etched onto a wafer, the greater the number of transistors per chip, and also the faster those chips are able to run.

As an example of the rate of technological change in this area, Figure 7 shows the evolution of Intel microprocessors by speed (as measured by megahertz) for different chip families. The speed of the chip is not equal to its processing power, especially when you compare the speeds of the chip across two processor families.[27] However, at least by this imperfect measure, it does appear that there was some pickup in the pace of technological change in the late 1990s. Between 1984 and mid-1997, the average speed increased at an average pace of 1.9 percent per month. From 1997 to December 2000, the pace more than doubled to 4.6 percent. Since then, the pace has fallen back to about 2.5 percent per month. Another dimension of microprocessors is the number of transistors. By this measure, between 1985 and 1997, the number of transistors per chip increased by about 32 percent per year. From 1997 to early 2004, the pace had picked up to almost 60 percent.[28]

FIGURE 7
PROCESSOR SPEED BY INTEL PROCESSOR FAMILY AND DATE OF INTRODUCTION (MEGAHERTZ)



Source: Intel.

23. McKinsey (2001) reaches a similar conclusion. McKinsey found that there was an acceleration in productivity in producing PC units, but that this acceleration had a fairly small effect on the acceleration of price declines of computers.

24. McKinsey (2001) claims that the change in the rate of price decline for MPUs is the main reason for the acceleration in price declines for semiconductors. However, AFK use a different, and likely better, measure for memory prices and that is why there is a difference in their conclusions.

25. In terms of technological innovations, these two classes of chips are often at the frontier. Two specific measures that are tracked and receive a fair amount of attention are gate length (for MPUs) and metal half pitch (for DRAMs and MPUs).

26. It is also interesting to note that this acceleration was somewhat unexpected. Throughout the 1990s, the ITRS projections for the pace of technological change consistently proved to be too conservative.

27. There are many ways to measure the processing power of chips. However, finding a consistent method over time is difficult, as new tests have been developed. Additionally, there are other dimensions to a chip's performance than its clock speed. For example, in the past several years, Intel has introduced a number of chips that contain features such as wireless networking and power saving. See "Why Speed Isn't Everything," *The Economist,* March 11, 2004.

28. Another reason why microprocessor prices fell especially quickly during the late 1990s is because profit margins may have shrunk. Aizcorbe, Oliner, and Sichel (2003) found that price-cost margins for Intel did indeed fall, and that the reductions accounted for about one-quarter of the acceleration in price declines. Yet another reason why MPU prices fell so quickly is that increased competition might have prompted firms to develop and release new products faster than they otherwise would have, a story touted by McKinsey (2001). Throughout the 1990s, the time it took Intel's primary rival, AMD, to produce a chip comparable to Intel's leading-edge chip steadily shrank. In response, the story goes, Intel made more frequent releases, increasing the share of chips being sold that were close to the leading edge.

Another major component of computers are rigid disk drives, an area where there has been tremendous technological change, but that, for some reason, does not get the attention that is bestowed upon semiconductors. In terms of technological change, according to Grochowski and Halem (2003) the areal density (how much information can be placed on a given area, such as megabytes per square inch) of drives doubled about every three years before 1991. Between 1991 and 1997, the areal density doubled about every two years, and since 1997 the areal density has been doubling every year. Unfortunately, what has been happening to prices during the 1990s and this decade is less than clear. According to the BLS, prices for computer storage follow a different pattern; prices for computer storage devices fell at 16–18 percent rates between 1995 and 1997, but prices fell only 9 percent on average from 1999 to 2000. However, according to Grochowski and Halem (2003), the declines in prices as measured in price per megabyte did accelerate in the late 1990s for desktop, mobile, and server hard drives. They find that not only has density been increasing sharply, but seek and access times have also been steadily decreasing.[29]

6.2. Communications Equipment

The 1990s witnessed tremendous technological change in communications equipment; computer networks grew ever more powerful, cellular phone networks were built out and upgraded, and there were tremendous advances in fiber-optic technology. In contrast to computer prices, however, prices for communications equipment fell only a touch, according to official statistics. Independent research has found potentially more believable results for the prices of communications equipment; Doms (2003) finds that prices fell considerably faster than the official measures and that the decline in prices appeared to pick up steam in the late 1990s and into 2000.

One reason for this acceleration in price declines was that prices for fiber-optic equipment started falling very quickly while the importance of fiber-optic equipment was increasing. Fiber-optic technology made several large advances in the 1990s, perhaps the most important of which was dense wave division multiplexing (DWDM). Before 1996, only a single light wave (also known as a channel) could be transmitted on a glass fiber. In 1996, a DWDM system could transmit eight channels simultaneously, with each channel carrying up to 2.5 gigabits per second (Gb/s), yielding a capacity of 20 Gb/s. By 2000, the capacity of DWDM systems increased twenty times; in 2000, there were DWDM systems that could transmit 160 channels simultaneously, producing a total capacity of 400 Gb/s. Therefore, between 1996 and 2000, the capacity of leading-edge DWDM systems increased at an annual rate of 115 percent. The pace of change has appeared to slow some since 2000; today there are systems that can carry 160 channels, each transmitting 10 Gb/s for a total capacity of 1.6 terabits per second, an average annual rate of increase of close to 60 percent.

Another area where technology improved rapidly during the 1990s was in local area network (LAN) equipment. Doms and Forman (2003) estimate that prices for LAN equipment fell at double digit rates during the latter half of the 1990s. Also, like computers, the prices of semiconductors that go into communications gear fell quickly. AFK estimate that prices for chips that are used in communications gear fell significantly faster during the late 1990s (23.7 percent) than during the early 1990s (3.4 percent). Unfortunately, the AFK study does not examine prices after 1999.

6.3. Software

Since 1990, software has consistently been the largest component of IT investment. Unfortunately, software has also been the least studied in terms of technological change and prices. This is especially unfortunate because there seems to be an incongruity in that software has gotten much better, but prices for software (as shown in Table 1) have not changed greatly. Although measurement problems exist for software prices used in national statistics, some independent information on software prices also has found that price changes have been fairly subdued compared to price changes for computers. For instance, Abel, Berndt, and White (2003) found that prices for Microsoft Office products fell an average of only about 5 percent per year between 1993 and 2001.

However, one must wonder if these results are consistent with the value that improvements in software have generated. A price index can show how much money is needed today to be as well-off as at some time in the past. During the 1990s, especially the latter half, there were monumental changes in PC software, though changes so far this

29. Not only is the cost per megabyte decreasing at rapid rates, but other factors that influence the total costs associated with hard disk drives have been falling as well, including power consumption and the physical volume of the drives. The trends of these series are described in Grochowski and Halem (2003).

decade seem to have slowed.[30] The primary PC operating system went through a series of changes, with Windows 95 (shipped in mass in 1996) ushering in a much better graphical user interface (GUI) than previous versions (Apple operating systems aside), and Windows 98 providing a more stable platform. PC programs that exploited the Windows GUI also garnered wider scale acceptance. Perhaps one of the most important technological revolutions in software was web browsers, which were first developed in the early 1990s but did not gain widespread acceptance until the latter half of the 1990s. Given these radical changes, how much money would have been required ten years ago to make us as well-off today in terms of software? According to the official data, the answer is that we would have needed only 8 percent more money in 1993 than we do today, which seems far off the mark.

Therefore, it could very well be the case that prices for software fell faster than the official data suggest, especially in the late 1990s when large advances in technology were made. However, the story of what has happened to innovation in PC software since the late 1990s is less clear. One anecdote reports that one-quarter of PCs still run Windows 98, an indication that there is at least one group of consumers that does not place much value on Microsoft's Windows XP offering in 2001; that is, the increment in technology between Windows 98 and Windows XP is not as great as the leaps from Windows 3.1 to Windows 95, and from Windows 95 to Windows 98. Looking ahead a little bit, Microsoft is not planning to update its operating system significantly until 2006. With all of that said, PC operating systems are just one small piece of the software pie, therefore caution should be used in extrapolating these observations too far.

7. Summary and Looking Ahead

The previous sections have laid out what happened to IT investment and what a fairly sophisticated model would have predicted for investment, followed by some cursory analysis of some common reasons given for the swings in investment. One of the primary reasons for going through these exercises is to provide some quantitative guidance as to what reasons seem the most likely, so that we may have a better idea of what lies ahead.

The most important message to take away from this analysis is that the main driver for real IT investment is prices; prices for IT goods have fallen considerably over time, in contrast to the tepid increases in prices for other investment goods. Prices for IT goods fell extremely fast in the late 1990s, pulled down by large drops in the prices of computers. Computer prices themselves reflect what happened to prices of their components, notably semiconductors and hard drives. The pace of decline in semiconductor prices picked up steam in the second half of the 1990s, reflecting very rapid rates of innovation in the semiconductor industry. The pace of innovation also picked up for hard drives. Elsewhere in the IT field, the pace of technological advances quickened in the area of communications equipment, especially for fiber-optic equipment and also, arguably, for computer software.

This paper also looked at some reasons that may have contributed to the large swings in IT investment around the turn of this century. For instance, the Y2K problem likely played only a minor role in the swings in IT investment. The dot-com boom and bust likely played a larger but still minor role. A sector that played a more significant role was the telecommunications sector, which was plagued by high expectations and a spectacular crash. The telecom crash placed a severe drag on IT investment in 2001 and again in 2002. Elsewhere in the economy, it is difficult to find excess ebullience in IT investment; in fact, the stellar productivity performance of the U.S. economy, especially in those sectors that invested heavily in IT goods, may suggest that firms, on average, did not overspend on IT.

Another reason for the large swings in IT investment could be that service lives of computers, especially personal computers, were shortened in the late 1990s in response to changes in the demands of software and also because of the rapid changes in the technology of computers themselves. So far this decade, service lives may have been extended once again, acting as a drag on IT investment. Although this story has some intuitive and anecdotal appeal, it is extremely difficult to quantify.

7.1. Looking Ahead

Technological change has been the driving force behind the high rates of investment in IT goods. Therefore, in looking at IT investment, it is important to think about what technological changes might lie ahead. One way to address this issue is to ask what factors generated the boom in innovation in the IT area and to ask to what extent those factors will be present in the future. Another method is to look at specific areas of technology and ask what innovations are likely to develop. Approaching the problem in both ways yields similar tentative conclusions: the future of innovation in IT looks fairly bright.

30. Unlike some semiconductors and communications gear, it is extremely difficult to measure technological changes in software. Measures of program size, say, in terms of lines of codes is not necessarily a good indicator, as large programs could simply be poorly written.

One reason for hope about future innovation in IT products is the amount of R&D that has been and is being spent. The latest official data from the National Science Foundation go through 2001. As seen in Table 2, R&D by companies in the IT industry grew sharply in the latter part of the 1990s and stood at record levels in 2001, totaling over $56 billion and making up almost one-third of all company-funded R&D. Based on reports, it appears that U.S. publicly traded companies did cut back on R&D some in 2002 (perhaps around 4 percent) and a bit further in 2003, but the level of R&D spending appears only to be a touch below the high levels posted in 2000.

Another hopeful sign is that the semiconductor industry expects to continue to make advances in the next several years, which in turn will help propel advances in computing and communication technologies. The ITRS, 2003 Edition, sponsored in part by the Semiconductor Industry Association, lays out what the industry expects in terms of advances and where major roadblocks may arise. The industry expects continued improvements throughout this decade, namely in the traditional areas of decreased feature size and increased performance. However, the pace of innovation may slow some. For certain chip features, the rate of decline in feature size may revert back to a three-year technology node cycle from a two-year cycle. Likewise, advances in storage technology are expected to continue at a very high rate well into the next decade, but perhaps not at the blistering pace that has been witnessed over the past several years (Grochowski and Halem 2003).

Another area of innovation that is receiving a tremendous amount of publicity is nanotechnology, an amorphous field that seems to include items such as very thin pieces of fiber-optic cable, small molecules that could be used in disease detection, new superconductors, solar cells, memory devices, and so on.[31] Although there has been a fair amount of attention given to nanotechnology, commercial products that use the technology are in short supply. Perhaps a word of caution is in order; carbon nanotubes once were touted as a potential replacement for steel and as an efficient conductor of electricity. However, since they were first developed in 1993, they have yet to be used in a widespread commercial application. The hype around nanotechnology resembles the hype around biotechnology over the past two decades; biotechnology has made some significant contributions to the health sciences, but it remains a small part of the economy and overall drug market.

Table 2
Company-Funded R&D Expenditures, 1997–2001
($ Billions)

	1997	1998	1999	2000	2001
IT equipment	25.0	26.4	21.3	29.4	34.9
Computers	7.7	8.3	4.1	5.2	5.2
Communications	2.8	8.4	5.8	11.1	15.2
Semiconductors	14.0	9.1	10.6	12.8	14.2
Other	0.5	0.6	0.8	0.3	0.3
IT services	10.2	12.0	14.9	17.5	21.7
Software	7.2	9.2	10.9	12.6	13.0
Computer design	3.0	2.9	4.0	4.9	8.7
Total IT R&D	35.2	38.4	36.2	46.9	56.5
Total R&D	133.6	145.0	160.2	180.4	181.6
IT share of total	26.4%	26.5%	22.6%	26.0%	31.2%

Sources: National Science Foundation and Department of Commerce (2003).

In terms of communications equipment, there are currently several struggles going on. One is related to extending the reach of long-haul networks to homes and businesses, the so-called "last mile" problem. Given the Gordian Knot that currently plagues the telecom regulatory environment, it is difficult to foresee when broadband services that exceed the current cable and DSL standards will become widespread. A second issue regarding the telecom industry is the evolution of wireless standards. There is far from universal agreement on what future networks will look like and when they will be deployed.

In summary, the future of IT investment looks bright, although perhaps not as bright as it did in the late 1990s. The most important force in IT investment has been the large drops in prices brought about by technological progress. There are several reasons to be optimistic about the future for technological progress in the IT area; firms continue to spend large sums on R&D, and rapid rates of innovation are expected to continue in several areas. No doubt there will be other areas as well where technological change will greatly reduce prices, and hence boost investment, for some time to come. Additionally, it appears that the economy is proving very adept at translating its IT investments into increased productivity.

31. See *The Economist*, "Beyond the Nanohype," March 13, 2003.

Appendix
Investment by the Telecom Service Industry

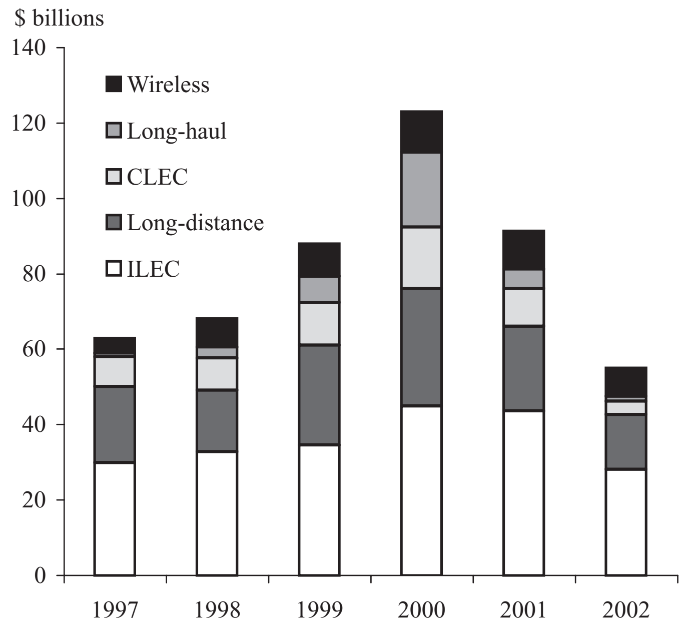
A number of factors contributed to the swings in investment in the telecom industry, including regulatory changes, new technology, and excess entry. As a first step in trying to understand what happened to the telecom service industry, each publicly traded company is placed into one of five categories: former Baby Bells (also known as incumbent local exchanges (ILECs)) competitive local exchanges (CLECs),[1] long-haul backbone providers (firms that specialized in deploying large-scale fiber-optic networks), long-distance companies (firms primarily in the long-distance voice and data business),[2] and wireless networks (cellular phone companies).[3]

Figure A.1 shows capital investment for each of these five categories between 1997 and 2002. An interesting note is that each of the five segments within the telecom service industry boosted capital spending between 1997 and 2000, only to be followed by sizable declines through 2002. The segment that has been the most consistent in its capital spending is the wireless networks; the nation is now criss-crossed with six nationwide wireless networks using three different technologies.

The two segments that epitomize overinvestment are the CLECs and the long-haul providers. Many CLECs entered the market after the 1996 Telecommunications Act, hoping to be able to lease equipment and facilities from the ILECs while providing services to businesses and consumers. The outlooks for this industry were hopeful, but for a variety of reasons many CLECs did not survive. From its peak in 2000, capital spending by CLECs fell by nearly 80 percent in 2002.

The segment that experienced the largest increase in capital spending in both percent and absolute terms was the long-haul industry, which also holds the distinction of having the largest decrease in both percent and absolute terms. The long-haul providers specialized primarily in deploying fiber-optic networks throughout the country and, in some cases, around the world. In the mid- to late 1990s and into 2000, there was significant entry into the market and massive increases in the amount of fiber that was laid in the ground. For instance, in 1990, there were four firms with nationwide fiber networks, but by 2000 there were ten.[4]

Figure A.1
Capital Spending by Telecommunications Service Providers, by Type of Provider



Additionally, in 1996 there were 143,000 route miles of fiber in the country, but by 2000 this had increased to 320,000.[5]

One reason for the massive increase in the capacity of the long-haul network was bullish expectations for future demand. For instance, a CEO of Level 3 Communications, a large long-haul firm, stated that Internet traffic would double every three to four months.[6] That didn't happen, and estimates are that demand (in terms of volume of data, not in terms of dollars spent) may be doubling every year, which is a significant increase but is substantially shy of expectations.[7,8] The high expectations were based in part on assumed rapid development and adoption of new technologies (such as deployment of high-speed cellular phone service) and widespread broadband access for homes and

1. In this methodology, I use the CLEC category as a residual from the other four groups.

2. AT&T, MCI-Worldcom, and Sprint FON group are the three largest firms in the group.

3. Some firms straddle these groupings. For instance, Verizon is a traditional ILEC but also has the nation's largest wireless network. I classify each firm in the sample into the category where it received the most revenue.

4. A nationwide network is defined here as having more than 10,000 route miles of fiber.

5. This information came from KMI Research and from company reports.

6. Many people cited this statistic, although the original source is hard to verify. For a history of the use (misuse) of such statistics, see "Fallacies of the Tech Boom," *Wall Street Journal*, September 26, 2002.

7. Doubling every four months is the same as increasing by a factor of 8 per year, and doubling every three months is the same as increasing by a factor of 16 every year.

8. See Coffman and Odlyzko (2002) for an analysis of the estimates for Internet traffic.

businesses. However, the rollout of new technologies and the growth in broadband access has been slower than the industry anticipated.

Another reason why the industry overbuilt touches upon four areas of economics: network economics, patent races, large fixed costs, and technological change. In terms of network economics, a fiber network that reaches twenty points is more valuable than two separate networks that reach only ten points each—the whole is worth more than the sum of the pieces. Therefore, if a firm decides to build a fiber network, then it will build a large network. In terms of patent races, firms entered the market hoping to finish their networks before their competitors; the firm that completed its network first would, if expectations were correct, win the race. In this case, there can be too much duplication of effort. For example, Chicago and Minneapolis are each served by twenty long-haul firms, Kansas City by fifteen, and St. Louis by fourteen. In 1990, these cities each were served by about five carriers.

Another factor that contributed to the glut of fiber in the ground is that the marginal cost of fiber is small relative to the cost of laying a new fiber route; in other words, it would be much cheaper to lay additional strands of fiber today while trenches are open than to dig up the trenches again several years from now and lay some additional fiber lines. So, although the utilization rate is low, that does not imply that firms were irrational in the amount of fiber they installed. Finally, as discussed in Section 6.2, astronomical increases in the amount of information that could be transported over a piece of fiber in the late 1990s because of DWDM technology reduced the amount of fiber needed.

In summary then, the telecommunications sector contributed significantly to the boom and bust of IT investment (especially the bust) because of a wide array of factors, including extremely high expectations about future demand that were not met. Looking ahead, there is much confusion over what new technologies will become available and whether and when they will be deployed.

References

Abel, Jaison R., Ernst Berndt, Alan G. White. 2003. "Price Indexes for Microsoft's Personal Computer Software Products." NBER Working Paper 9966.

Aizcorbe, Ana, Kenneth Flamm, and Anjum Khurshid. 2002. "The Role of Semiconductor Inputs in IT Hardware Price Decline: Computers vs. Communications." Board of Governors of the Federal Reserve System, Finance and Economics Discussion Series 2002-37. http://www.federalreserve.gov/pubs/feds/2002/200237/200237abs.html

Aizcorbe, Ana, Stephen Oliner, and Daniel Sichel. 2003. "Semiconductor Price Puzzles." Unpublished working paper.

Basu, Susanto, John Fernald, Nicholas Oulton, and Sylaja Srinivasan. 2003. "The Case of the Missing Productivity Growth: Or, Does Information Technology Explain Why Productivity Accelerated in the United States but Not the United Kingdom?" Federal Reserve Bank of Chicago Working Paper 2003-08. http://www.chicagofed.org/publications/workingpapers/papers/wp2003-08.pdf

Coffman, K.G., and A.M. Odlyzko. 2002. "Internet Growth: Is There a 'Moore's Law' for Data Traffic?" In *Handbook of Massive Data Sets,* eds. J. Abello, P.M. Pardalos, and M.G.C. Resende. Dordrecht: Kluwer, pp. 47–93.

Council of Economic Advisors. 2003. *Economic Report of the President 2003.*

Department of Commerce. 1999. "The Economics of Y2K and the Impact on the United States." Economic and Statistics Administration. http://www.esa.doc.gov/Y2.cfm

Department of Commerce. 2003. "Digital Economy 2003." Economic and Statistics Administration. http://www.esa.doc.gov/DigitalEconomy2003.cfm

Doms, Mark. 2003. "Communications Equipment: What Has Happened to Prices?" Forthcoming in *Measuring Capital in the New Economy.* Chicago: NBER/CRIW, University of Chicago Press.

Doms, Mark, Wendy Dunn, Steven Oliner, and Daniel Sichel. 2003. "How Fast Do Personal Computers Depreciate? Concepts and New Estimates." Forthcoming in *Tax Policy and the Economy,* Volume 18, Cambridge, MA: MIT Press.

Doms, Mark, and Christopher Forman. 2003. "Prices for Local Area Network Equipment." Federal Reserve Bank of San Francisco Working Paper 2003-13. http://www.frbsf.org/publications/economics/papers/2003/wp03-13bk.pdf

Gordon, Robert. 2003. "Exploding Productivity Growth: Context, Causes, and Implications." Forthcoming in *Brookings Papers on Economic Activity.*

Grochowski, Edward, and Robert Halem. 2003. "Technological Impact of Magnetic Hard Disk Drives on Storage Systems." *IBM Systems Journal* 42(2).

International Technology Roadmap for Semiconductors. 2003. http://public.itrs.net/Files/2003ITRS/Home2003.htm

Jorgenson, Dale, Mun Ho, and Kevin Stiroh. 2002. "Growth of U.S. Industries and Investments in Information Technology and Higher Education." Forthcoming in *Measuring Capital in the New Economy.* Chicago: NBER/CRIW, University of Chicago Press.

Kiley, Michael. 2001. "Business Investment in the Federal Reserve Board's U.S. Model (FRB/US): Specification and Implications." Unpublished memo, Federal Reserve Board of Governors.

McKinsey Global Institute. 2001. "U.S. Productivity Growth, 1995–2000." http://www.mckinsey.com/knowledge/mgi/productivity/

McKinsey Global Institute. 2002. "How IT Enables Productivity Growth." http://www.mckinsey.com/knowledge/mgi/IT/

Oliner, Stephen, and Daniel Sichel. 2000. "The Resurgence of Growth in the Late 1990s: Is Information Technology the Story?" *Journal of Economic Perspectives* 14 (Fall) pp. 3–22.

Oliner, Stephen, and Daniel Sichel. 2002. "Information Technology and Productivity: Where Are We Now and Where Are We Going?" Federal Reserve Bank of Atlanta *Economic Review* 87 (Summer) pp. 15–44.

Whelan, Karl. 2000. "Computers, Obsolescence, and Productivity." Board of Governors of the Federal Reserve System, Finance and Economics Discussion Series 2000-6. http://www.federalreserve.gov/pubs/feds/2000/200006/200006abs.html

Recent Productivity Growth: The Role of Information Technology and Other Innovations

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This article is based on the keynote address delivered in November 2003 at the conference organized by the Federal Reserve Bank of San Francisco's Center for the Study of Innovation and Productivity on "Technology, Productivity, and Public Policy."

I am pleased to be talking about one of the truly salient issues for the economy today to such a distinguished audience. The acceleration in productivity growth since the mid-1990s has been an exceptionally important development for the U.S. economy. My remarks are going to run somewhat contrary to the view that information technology has been the overwhelming impetus to the acceleration in productivity growth in recent years. While technology and in particular information technology (IT) are obviously very important drivers of productivity, I want to make the case that perhaps they have been overemphasized in the literature. This might sound a little subversive in the context of this conference; but it really is not, since my comments are entirely consistent with the broader theme running through the sessions, that productivity is linked to innovation.

A considerably less controversial point now is that productivity growth has accelerated. Obviously, there was a period when we wondered if the increase in productivity growth starting in the mid-1990s was just a cyclical effect. Now that concern seems to have gone away, in part because measured productivity growth now is even faster than it was from 1995 to 2000. Whether that will survive data revisions and changes in measurement methodologies remains to be seen. However, unless there are drastic revisions, it certainly looks as if the higher rate of productivity growth is staying around for a while.[1]

Has the Contribution of IT Been Overstated?

One of the reasons that the contribution of IT to growth may have been overstated is that the main tool by which we judge such contributions is growth accounting. This is obviously a valuable tool, but it has some pitfalls; in addition, it requires careful interpretation as to what it actually says about the recent growth period.

In concept, growth accounting is straightforward—it is a framework for allocating the growth in output to the growth in capital (plants, equipment, and software), the growth in labor, and the growth in total factor productivity (TFP). In principle, growth in TFP stems from improvements in the ways capital and labor are combined in production processes. This might be thought of generally as changes in how workplaces are organized and managed.

In practice, however, we know that measured growth in TFP is affected by the errors in measuring capital and labor inputs. The potential mismeasurement of IT investment is one of the pitfalls of relying on growth accounting that I will come to in a bit. First, I'd like to discuss other reasons to be careful about the empirical results relating to the 1990s experience that use growth accounting measures, especially ones using aggregate data for a single country.

One reason for caution is that the growth accounting results from the 1990s reflect the fact that there was essentially a "one-observation" correlation in the aggregate data: IT investment and labor productivity accelerated at about the same time. This convinced many people that the two events were related as cause and effect—the productivity acceleration must have been driven by IT investment.

1. Fuller discussion of the issues discussed in this article can be found on the website www.iie.com.

However, before the 1990s productivity speedup, there was the 1970s productivity slowdown. Measured labor productivity growth went from an average of 2.8 percent during the period spanning the 1950s through the earlier 1970s, to an average of about 1.4 percent from 1973 to 1995. During the sessions at this conference, there were discussions about the host of reasons given for the slowdown. The one that was certainly the most popular when it was proffered in the 1970s was that the productivity growth slowdown was caused by the rise in oil prices. At that time there was a different one-observation correlation: productivity slowed down and energy prices went up at about the same time. Many people, me included for a while, believed that higher energy costs had caused slower productivity growth. It was not a crazy idea; indeed, there were good arguments, such as that rising energy prices would cause labor productivity growth to slow down because labor would be substituted for energy-using capital. There were also objections to that story, of course, but what really caused the collapse of the energy–productivity story is that oil prices came back down in the 1980s and there was little or no improvement in trend productivity growth. That experience should sound a warning that one-observation correlations can easily collapse when a second observation comes along.

Another reason for caution in linking IT investment to the post-1995 productivity acceleration is that the growth accounting framework did not do very well in tracking productivity movements prior to 1995. There was a fair amount of IT investment going on well before 1995. Indeed, that investment inspired the famous Solow paradox—Robert Solow quipped in 1987 that he could see computers everywhere except in the productivity data. Moreover, we now seem to be dealing with the reverse of the paradox: there was a severe slump in technology spending that began in 2000 and lasted into 2003, yet productivity growth has remained strong and may even have accelerated; from the first quarter of 2001, which is roughly the official cyclical peak, through the third quarter of 2003 productivity growth averaged over 4 percent a year. Later on I will talk about how investment in intangible capital may help, at least in part, to resolve this paradox. However, as with the oil price story, on the surface there appears to have been a breakdown in the one-observation correlation between the productivity growth trend and its apparent driver.

A second concern about taking the growth accounting results at face value is the possibility of reverse causality in the 1990s. To a degree, it may have been the economic boom that created the big wave of IT investment rather than the wave of IT investment that created the boom. Investing in IT became the thing for companies to do. Profits were strong and IT managers had considerable influence over investment decisions. Hardware and software vendors hyped the benefits of their products, and no CEO wanted his or her company to be left behind in the high-tech boom. Some of that investment did pay off in higher productivity, but there may have been a systematic tendency to overinvest. Expected returns were higher than actual returns over this period—hence, in part, setting the stage for the technology bust after 2000.

This latter concern, of course, is not directly related to any shortcomings of growth accounting, per se. Indeed, growth accounting is part of the basic tool kit of economics and is firmly established as a valid approach. So let me explain why I have reservations about taking its findings at face value. Here we get back to the issue of mismeasurement. The first question is whether or not to believe what the computer price deflators are telling us. Is it really true that quality-adjusted computer prices are falling rapidly, or are there problems in the methodology used for their estimation? There have been questions raised about the hedonic approach, but this does not seem to be a key issue quantitatively. The computer price deflators are built not only from hedonic regressions but also from matched models. The matched model approach follows the price over time of the same computer or compares prices in different periods for computers that are functionally very similar. In addition, the price indexes based on the matched model approach have fallen about as fast as the prices based on hedonic regressions. It really does seem to be the case that quality-adjusted computer prices have fallen extraordinarily fast.

Nevertheless, it still is fair to ask whether the price deflators accurately reflect the effective use-value of IT capital in the production process. Many of us have voiced skepticism based on anecdotal evidence. Robert Gordon (2000) has argued that the latest version of Word run on the latest model computer does not do that much more than the previous version and does not increase the computer user's productivity by very much. Going beyond anecdotal evidence, one of the McKinsey Global Institute (2002a) case studies examined what happened when banks invested in new generations of faster, more powerful computers. The McKinsey team found that most of the lower-skill and middle-level employees (tellers, for example) were doing pretty much the same things in the same way with the new computers as with the old computers. The banks reported little productivity gain in their retail operations from upgrading their computer hardware.

If this case study evidence is correct, however, it poses an important puzzle. If the new computers and software yielded little in the way of productivity benefits, why did the banks invest so much in them? Both the hedonic approach to computer price measurement and the matched model approach reflect what customers (businesses or individuals) are willing to pay to get the latest technology. If people are willing to spend their own money to buy new hardware, they must expect a gain from the purchase. Is there some systematic bias or failure of expectations that could explain this puzzle? Or are we missing a dimension of the decisionmaking?

Part of the answer may be that it is difficult to infer the use-value of investments when there are network effects, and computer technology is one area where these effects are important. The value to a business (or to a consumer) of a computer depends a great deal on the compatibility of that computer with other people's computers. One reason that banks put very high-powered computers on the desks of all of their employees is that they follow replacement cycles. After a period of time some computers wear out and, more importantly, some computers become obsolete in that they are not able to meet the high-end technology needs of some employees. To maintain internal compatibility, a company undertakes a comprehensive upgrade so that the speed of the convoy, if you like, is pulled along by the fastest ship rather than going at the speed of the slowest ship. The reason a low speed computer enters with a very low price when the Bureau of Labor Statistics collects its data is that many firms cannot choose to buy the less powerful computer since it would not be compatible with their other computers or with the software in use throughout the company. And the issue of compatibility may also extend outside a specific company to its suppliers or customers.

This argument is suggestive but not proven. Still, in the presence of strong network effects, it is very difficult to assess the benefit of IT investment to one part of a business enterprise without considering the enterprise-wide effects. In the case of IT investment by banks, for example, we need to know the impact on productivity if lower-skilled and middle-level employees were to continue to use less powerful computers while the rest of an organization upgraded its IT hardware and software.

Insights from the Use of Disaggregated Data

The severity of the pitfalls for empirical analysis I have mentioned are mitigated to some extent in studies that use disaggregated data. There are a number of excellent studies that use industry level data, but rather than going through a full literature review, let me mention work by Kevin Stiroh and by Dale Jorgensen, along with a paper that I wrote with Robert Lawrence.[2] These papers suggest that industries that had invested in IT hardware had indeed achieved faster productivity growth than other industries in the 1990s and had achieved greater productivity acceleration after 1995. Not all the industry evidence point the same way, however. In particular, an article by Jack Triplett and Barry Bosworth (forthcoming) finds that the industries that had surges in labor productivity growth were not necessarily the industries that had surges in IT investments. Rather, more of the post-1995 increase in labor productivity growth on an industry level seemed to come from TFP than from investment in IT. They were using the growth accounting framework at the industry level and, not surprisingly given the aggregate results, they did find that IT contributed to productivity in the 1990s as a whole. What they did not find at the industry level was that IT contributed especially to the post-1995 acceleration.

Going below the industry level, a study by Lucia Foster, John Haltiwanger, and Cornell Krizan (2002) finds that the exit of low-productivity establishments and the entry of high-productivity establishments generated most of the gains in retailing. That is a strong result, and it raises questions about the impact of IT. It suggests that investment in IT within existing retail establishments was not the main source of productivity increases in that industry. This is a notable result since retailing is a sector that has made one of the biggest contributions to overall productivity growth in recent years.

Key Drivers of Innovation: IT and Competitive Intensity

Detailed industry case studies also can shed light on the role of IT, especially how it is used in the business setting. I will use the case study evidence from the work carried out by the McKinsey Global Institute (2002a). Let me reiterate: I do not want to make the argument that IT investment was all a failure or that it contributed nothing to productivity growth. My comments are intended to shift the debate away from an uncritical acceptance of the idea that IT investment has been the dominant driver of faster productivity growth.

The analysis from the McKinsey case studies suggests that there is not one simple paradigm that can describe how IT affects business production processes and productivity. They looked at examples where IT investment did have a positive impact on productivity and found that the IT applications were used in very different ways across industries and even within subcategories of an industry. For example, in retailing, the mass-market supercenter, big box discounters, such as Wal-Mart and Costco, used IT to improve their supply chains and to allow the stores to manage their inventories, purchasing, etc., more effectively. Among spe-

2. See, for example, Stiroh (2002), Jorgensen, Ho, and Stiroh (2004), and Baily and Lawrence (2001).

cialty retailers, such as J. Crew and The Limited, IT allowed the stores to track changing customer tastes and match their own inventory mix to stock the right products for their customers (making sure the "hot" products are on the shelves). In both of these examples, IT is used to improve the supply chain, but it is serving a different role in each. For the discounters, its purpose was primarily to cut costs, allowing the stores to sell at lower prices. For the specialty stores, it allowed them to sell higher margin items with greater value-added.

Earlier I talked about banks and the apparent low returns they obtained from one part of their IT investment. Some of their investments clearly succeeded, however. Over the course of the 1990s, banking organizations saw a massive increase in the number of phone requests and inquiries from their customers (the number of phone inquiries rose from just over 1 million in 1994 to 2.3 million in 1998, a 24 percent annual rate of growth). The banks made major investments in computerized voice response units to handle the growth of calls. Customers would rather talk to a person than a machine, but without the greater use of IT, banks would not have been able to provide the same level of service profitably. There was, in fact, a large increase in the number of people employed to handle calls, as well (employment in this activity grew at 13 percent a year between 1994 and 1998). But it would have taken an even larger increase in personnel to handle all of the calls personally. With the IT investment, banks were able to expand their services and, at the same time, sustain overall labor productivity.

The design of chips is another example where the use of IT had a positive impact on productivity, but the way that was achieved is very different from the two previous examples. In developing a new chip, the constraint on performance improvement in the late 1990s was not merely the number of transistors that could be packed onto a chip. Over the long term, the ability to manufacture chips with greater technological capability (to keep Moore's law going) is obviously important. But at that time, the binding constraint was the ability of companies to design chips that took advantage of the capability that was available. The complexity of chip design had increased very rapidly, almost too rapidly for companies to deal with effectively. Consequently, it was developments in electronic design and testing tools that helped companies such as Intel improve productivity.

These are all examples of how IT investment paid off in higher productivity. There were a number of cases where the investment did not pay off. One example was already discussed, as banks upgraded the computers on the desks of tellers. Another example is investment in customer relations management software. As companies installed this software, they planned to collect reams of data on their customers that would allow them to customize their services. For example, customers would walk into a hotel, where employees would greet them personally, equipped with detailed information about what kind of rooms they liked and what services they might want. In some cases, the hardware and software were purchased but were never really put into operation because of data problems or other difficulties. In other cases the hotels were not able to generate higher revenues through using the systems—or at least they were not able to earn a positive return on their investment.

Another innovation, enterprise resource planning (ERP) software, has had mixed results. It has had some successes, as evidenced by the growth of SAP, one of the leading providers of this software. But many of the efforts involving ERP did not improve productivity. A key shortcoming is that ERP tends to lock in a certain way of doing things making innovation more difficult. Another problem with ERP is that the technology has had difficulty dealing with the degree of data incompatibility within many firms, so the promise of total information integration frequently was not realized.

The case studies, then, suggest that IT has paid off in some cases, but not in others. That is to be expected; after all, in any area, some projects will pay off and others will not. However, three important lessons emerge from the case studies. First, the examples where businesses were successful in their IT investment were ones where the companies had already identified a specific problem to be solved or opportunity to be exploited. They then looked at their business system to figure out how it could be changed to solve the problem or exploit the opportunity. Then, as part of that process, they figured out how IT investment could contribute to the success of the improved business system. Successful IT applications also typically occurred where outcomes could be quantified and monitored. The second lesson, as I stated earlier, is that when IT works, it can work very differently from industry to industry and even from firm to firm within an industry.

The third lesson is that, for many productivity-increasing innovations, IT investment was not the most important component. Take the case of the retail sector. Generally, companies can obtain labor productivity increases by building larger stores, such as the big box stores. They can also lower their costs by efficient national and global sourcing where, again, scale is an important benefit. Large purchasers are able to obtain lower prices from suppliers, thereby adding to their margins and value-added per employee. In retailing and many other industries, figuring out what consumers want and what they will pay for allows companies to develop new designs that add value to their products and increase productivity. The auto industry is such an example, where (for better or worse) companies realized that customers would pay premium prices for SUVs and minivans. By shifting the mix of their output, auto makers were able to increase their value-added per employee.

Let me clarify here. Clearly, IT has become part of the backbone of business operations, so it does have a role in all of the preceding examples; e.g., in the case of product design, computer-aided designs are important, so IT was certainly a facilitating technology for the innovations. But the key point is that the source of the productivity increase was not primarily major new IT investments, nor, I suspect, were these innovations driven to any great extent by the decline in computer prices.

In general, improvements in workplace organization that affect the way offices are run, the way work flows are organized, and the way workplaces are configured can often have very large payoffs in productivity; and they do seem to have done so, based on the industry case studies. Is there any unifying catalyst for such innovations? The one thing that comes through consistently is that competitive intensity puts a lot of pressure on companies to innovate and improve their productivity. One McKinsey Global Institute (2001) study suggested that this explains the acceleration in productivity that took place in the 1990s. That is a tough case to make, because there is no smoking gun that says competitive intensity suddenly strengthened in the mid-1990s. A better case to be made is that there was a lot of deregulation in the U.S. starting in the 1970s and continuing into the 1980s and 1990s that steadily increased competitive intensity. In addition, there has been a substantial increase in the volume of trade and the extent of globalization in the last twenty years, with a large volume of foreign direct investment coming to the U.S. in the 1990s. In a large country like the U.S., the benefits that are thought to come from globalization often occur as best-practice companies expand their operations throughout the country. It is the progression from regional competition to national competition that increases competitive intensity. In short, there is a pretty good case that competitive intensity in the U.S. economy was greater in the 1990s than in earlier periods, and competitive intensity remains high today.

It may simply be that the forces driving faster productivity growth after the mid-1990s—both IT improvements and increased competitive intensity—were building over a number of years and that business cycle effects or quirks in the data resulted in an apparent pickup in productivity growth starting in the second part of the 1990s. In reality, faster trend labor productivity growth may have been coming down the pipeline before 1995, masked perhaps in the early years of the decade by recession and then by very rapid job growth.

Intangible Capital

There is an emerging body of economics literature looking at investment in intangible capital, which is relevant for understanding productivity trends and for interpreting growth accounting results. Robert Hall, Eric Brynjolfsson, and Robert Gordon have all been leaders in this area. The existence and importance of intangible capital can be used to explain the Solow paradox of why productivity remained slow in the 1980s and early 1990s, even though computer investment was growing rapidly. And it can explain why productivity growth remained rapid after 2000, even though IT spending slumped.

The argument is that it takes time to learn how to apply new technologies effectively and that learning takes resources (people). The buildup in such knowledge is investment in intangible capital, and the resulting knowledge stock is part of an economy's intangible capital. Based on this view, the explanation for the Solow paradox is that, even though companies were investing in IT, measured productivity growth was not increasing because companies also were employing many people to figure out how to use the new technology and how to reorganize their companies to take advantage of the new technology. It was not until after 1995 that the payoff in increased productivity in business operations was large enough to offset the drag on measured productivity from the employees whose output was intangible capital investment. One way of looking at this is that there was (and still is) a measurement error. Spending on tangible capital is counted as investment in GDP, while spending on intangible capital is not.

After 2000, the effects went in the other direction. Under pressure to sustain profits, companies cut back drastically on their investment in IT and cut back similarly on their investment in intangible capital. Measured productivity soared as companies reduced employment, but this came at the price of reduced intangible investment. If this story is correct, then the prospects for future productivity growth may have been compromised. Companies are taking advantage of their past investments and are not building the basis for future growth.

This is an interesting and valuable story, and it can help explain some of the surprising shifts in productivity trends. In some ways it is quite consistent with the industry case study results described earlier. Productivity growth is not coming just from how many computers a company bought this year, or even the stock of computer capital. It also comes from how well companies use information technology. Further, intangible capital does not have to be associated only with IT. Investment in designing new business systems or reorganizing the workplace or developing new products or new markets all can be considered investments in intangible capital. For individual companies, investments in advertising and brand development are important sources of intangible capital. How these contribute to aggregate productivity is less clear.

There is no question that intangible capital is important. That part of the new thinking is solid.[3] The only question about this view is whether the new theory is being presented in quite the right way. One of the lessons from the case studies is that the companies that went out and bought IT and then sat down to figure out how to use it often did not succeed. The innovation should be the starting point, that is, when someone figures out how to improve operations or add value to a company's products. The IT investment that pays off is the investment that follows that innovation. Maybe this nuance would lead to the same place empirically, but it is important to get the story straight. In addition, there is skepticism among the business consultants that I talk to about whether the cutbacks after 2000 really involved the elimination of valuable intangible capital accumulation. The alternative view is that, in the downturn, companies eliminated low-return activities that probably should have been cut earlier (at least from the viewpoint of shareholders). Either way, there has been a one-off temporary surge in productivity, but this alternative view suggests this has not come at the expense of valuable investments in future productivity growth.

Lessons from Other Countries

In looking at what we have learned from the experiences of other countries, I am going to concentrate on Europe,[4] and the story for this region has been changing. There was a straightforward view a couple of years ago that said that productivity growth had not sped up in Europe after 1995; indeed, it may have slowed. At the same time, European businesses apparently had not invested in IT to the same extent as businesses in the U.S. These facts were very supportive of the hypothesis that IT investment had driven faster productivity growth in the U.S. and suggested that Europe needed to increase its IT investment to get on the same bandwagon.

Then new results emerged suggesting that, in fact, Europe had invested rather heavily in IT. Previous studies had underestimated the extent of European IT investment partly because the structure of that investment is different—a lot of in-house software development in Europe was not being reflected in IT spending data. In addition, not all European countries use price deflators that are comparable to those used in the U.S., which again resulted in an understatement of IT investment. Even after allowing for these factors, IT capital stock in Europe still is lower than in the U.S., and certainly IT production is lower. But the gap in IT use is not nearly as large as had been thought.

It is possible that, with further study and revised measurement, the picture we have of Europe will change again. But, based on my assessment of the current state of knowledge, what has happened in Europe is that businesses have greatly increased their use of IT; unlike the U.S., however, the European economies have experienced continued slow productivity growth (with some exceptions).[5] These findings indicate that rapid IT investment growth does not ensure rapid labor productivity growth.

Case studies of industries in France and Germany add to this picture.[6] If you look at the industry in these two economies where productivity grew fastest—mobile telecommunications—the gains are indeed related to IT. The technology became available, it became cheap enough to spread, and the industry grew very rapidly. Indeed mobile telecom productivity grew much faster in France than in the U.S. For that sector, measured labor productivity in France in 2000 was twice as high as it was in the U.S. This is not because the technology in France is particularly better. It is because the regulation of mobile telecom is better in France, which is unusual. In France, they have had about the right amount of competition in mobile telecom. In the U.S. in the 1990s there were too many small companies operating well below minimum efficient scale.

In most of the other case studies, IT did not play a major role in explaining differences in productivity growth among France, Germany, and the U.S. In retailing, productivity is not as high in Germany as it is in the U.S., even though many German retailers use IT in ways that are similar to businesses in the U.S. The difference in performance in retailing really has much more to do with the more limited access to land in Germany and the consequent inability to build big box stores.

Another example is where productivity in the automobile industry grew very fast in France, but not in Germany. That was because in France they were willing to undergo restructuring. In France, they decided to privatize the firms that had been state-owned, and this resulted in changes in management and an acceptance of the need for layoffs. Germany, in contrast, did not go through a similar restructuring; indeed, the German firms face restrictions on lay-

3. Of course the importance of intangible capital in the form of R&D investment has been appreciated for a long time.

4. See Baily and Kirkegaard (2004).

5. Recent work by the OECD (2003) has suggested that differences in measurement methods do not greatly change the standard results for aggregate labor productivity comparisons. These differences may change the industry distribution of growth.

6. See McKinsey (2002b).

offs. IT certainly is important to automobile manufacturers, whether in designing new cars or in using the computer-controlled assembly devices, but differences in the use of IT did not seem to account for differences in productivity growth between the countries in the 1990s.

Electric power is a case where Germany did pretty well in raising its productivity, though not necessarily through great investment in IT. Rather, it did so by privatizing the industry; and even before this occurred, the companies had been restructured in preparation for sale. Germany also changed the structure of regulation in the electricity industry. From the experience of California, we know that regulating electric power is not the easiest thing to do. However, if it is done correctly, there are tremendous gains from privatization and the right kind of regulation. That was the case in Germany, and it seems to have been the case for the United Kingdom also, after some false starts.

In summary, when industries are competitive and not overregulated in Europe, they use IT in ways that are similar to the same industries in the U.S. Differences in IT use came largely as a result of differences in industry structure and regulation, but were not, in any case, the main reason for productivity performance differences. I note that when these case studies were at an early stage, both the McKinsey consultants who did the research and I myself firmly believed that IT would explain much of the performance differences among the countries. As the work progressed, however, it became clear that the case study evidence would not support this view.

Conclusion

Let me bring the focus back to the acceleration of productivity in the U.S. Since the mid-1990s, the acceleration of productivity in the industries that produce IT hardware and the rapid investment in IT capital both contributed to the overall productivity acceleration. The need for businesses to build intangible capital to realize the potential from new technologies is important in understanding the pattern of productivity growth for the U.S. in recent years. Nevertheless, reliance on growth accounting likely has led to an overstatement of the impact of IT.

Productivity is driven by innovation, which may be strongly related to IT use, but often is not. A high level of competitive intensity is important in encouraging leading companies to innovate and in forcing competitors either to adopt the same innovations or to find alternative innovations if they are to survive.

References

Baily, Martin N., and Jacob Kirkegaard. 2004. *A Radical Transformation of the European Economy.* Washington, DC: Institute for International Economics.

Baily, Martin N., and Robert Z. Lawrence. 2001. "Do We Have a New E-Conomy?" *American Economic Review* 91 (May) pp. 308–312.

Foster, Lucia, John Haltiwanger, and C.J. Krizan. 2002. "The Link between Aggregate and Micro Productivity Growth: Evidence from Retail Trade." NBER Working Paper w9120 (August).

Gordon, Robert J. 2000. "Does the 'New Economy' Measure Up to the Great Inventions of the Past?" *Journal of Economic Perspectives* 14(4) (Fall) pp. 49–74.

Jorgensen, Dale W., Man S. Ho, and Kevin J. Stiroh. 2004. "Growth of U.S. Industries and Investments in Information Technology and Higher Education." In *Measuring Capital in a New Economy,* eds. C. Corrado, C. Hulten, and D. Sichel. Chicago: University of Chicago Press.

McKinsey Global Institute. 2001. "U.S. Productivity Growth, 1995–2000." *MGI Reports* (October). www.mckinsey.com/knowledge/mgi/productivity/

McKinsey Global Institute. 2002a. "How IT Enables Productivity Growth." *MGI Reports* (November). www.mckinsey.com/knowledge/mgi/IT/

McKinsey Global Institute. 2002b. "Reaching Higher Productivity Growth in France and Germany." *MGI Reports* (October). www.mckinsey.com/knowledge/mgi/europe/

OECD. 2003. *The Sources of Economic Growth in OECD Countries.* Paris: OECD.

Solow, Robert. 1987. *New York Review of Books* (July 12).

Stiroh, Kevin J. 2002. "Information Technology and the U.S. Productivity Revival: What Do the Industry Data Say?" *American Economic Review* 92(5) (December) pp. 1,559–1,576.

Triplett, Jack E., and Barry P. Bosworth. Forthcoming. "Baumol's Disease Has Been Cured: IT and Multifactor Productivity in U.S. Services Industries." *The New Economy. How New? How Resilient?* ed. Dennis W. Jansen. Chicago: University of Chicago Press.

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Progress Report

Performance in 2003. The Center's inaugural event was a two-day conference entitled "Technology, Productivity, and Public Policy," which was held in November 2003. More than 75 researchers from around the country attended. The topics related to measuring and understanding the relationships between innovation and productivity (see p. 67 for the conference agenda and p. 73 for a summary of the conference papers). Martin Baily, a senior fellow at the Institute for International Economics and a leading expert on these issues, gave the keynote address, which has been adapted for publication as an article in this issue of the *FRBSF Economic Review* (see p. 35).

CSIP hosted several visiting scholars and seminar speakers. The visiting scholars looked at issues related to workplace innovation and productivity (Sandra Black, UCLA), computer investment and productivity (Simon Gilchrist, Boston University), and patenting in the pharmaceutical industry (Margaret Kyle, Carnegie Mellon University). Among several seminar speakers were Robert Hunt (Federal Reserve Bank of Philadelphia) and Kevin Stiroh (Federal Reserve Bank of New York), who presented research on innovation and patenting and measuring trend productivity growth.

CSIP affiliates conducted active research programs in 2003, completing eight Working Papers. The range of topics included measuring innovation, pricing information technology goods, understanding productivity growth, and tracking the productivity–wage link (see the Working Paper Abstracts, p. 45). Affiliates also published six articles in the *FRBSF Economic Letter*; beginning in 2004, the *Letter* will include a special series, "CSIP Notes."

Plans for 2004. Plans for 2004 build on the expertise and momentum developed last year. In addition to continuing to support and publish affiliates' research in the Working Papers series and other publications, CSIP will expand its visiting scholar program, bringing in six to eight researchers for periods ranging from one week to one month. CSIP also is hosting a Joint Seminar Series on Innovation, Productivity, and Growth with University of California, Berkeley, and Stanford University, meeting seven times a year and bringing leading researchers to the Bay Area to present and discuss their research. The first speaker in the series was Edward Prescott of Arizona State University, speaking on "A Unified Theory of Evolution of International Income Levels."

Finally, in 2004, the Center launched a CSIP website (www.frbsf.org/csip), making the research and analysis done by CSIP affiliates available to the public. The website contains links to all the publications mentioned here, as well as data and charting applications and other features useful to both researchers and nonspecialists.

Working Papers Series Abstracts

Complete texts of papers in this series are available on the Bank's website at
http://www.frbsf.org/publications/economics/papers/index.html
Electronic subscriptions are available through this site; paper copies are no longer available.

WP 03-01

Robust Monetary Policy Rules with Unknown Natural Rates

Athanasios Orphanides, *Federal Reserve Board*
John C. Williams, *FRB San Francisco*

We examine the performance and robustness properties of alternative monetary policy rules in the presence of structural change that renders the natural rates of interest and unemployment uncertain. Using a forward-looking quarterly model of the U.S. economy estimated over the 1969–2002 period, we show that the cost of underestimating the extent of misperceptions regarding the natural rates significantly exceeds the cost of overestimating such errors. Naive adoption of policy rules optimized under the false presumption that misperceptions regarding the natural rates are likely to be small proves particularly costly. Our results suggest that a simple and effective approach for dealing with ignorance about the degree of uncertainty in estimates of the natural rates is to adopt difference rules for monetary policy, in which the short-term nominal interest rate is raised or lowered from its existing level in response to inflation and changes in economic activity. These rules do not require knowledge of the natural rates of interest or unemployment for setting policy and are consequently immune to the likely misperceptions in these concepts. To illustrate the differences in outcomes that could be attributed to the alternative policies we also examine the role of misperceptions for the stagflationary experience of the 1970s and the disinflationary boom of the 1990s.

WP 03-02

Human Capital and Technology Diffusion

Jess Benhabib, *New York University*
Mark Spiegel, *FRB San Francisco*

This paper generalizes the Nelson-Phelps catch-up model of technology diffusion. We allow for the possibility that the pattern of technology diffusion can be exponential, which would predict that nations would exhibit positive catch-up with the leader nation, or logistic, in which a country with a sufficiently small capital stock may exhibit slower total factor productivity (TFP) growth than the leader nation. We derive a nonlinear specification for TFP growth that nests these two specifications. We estimate this specification for a cross-section of nations from 1960 through 1995. Our results support the logistic specification and are robust to a number of sensitivity checks. Our model also appears to predict slow TFP growth well. Of the 27 nations that we identify as lacking the critical human capital levels needed to achieve faster TFP growth than the leader nation in 1960, 22 did achieve lower growth over the next 35 years.

WP 03-03

Mortgages as Recursive Contracts

John Krainer, *FRB San Francisco*
Milton Marquis, *Florida State University*

Mortgages are one-sided contracts under which the borrower may terminate the contract at any time, while the lender must commit to honoring the terms of the contract throughout its life. There are two aspects to this feature of the contract that are modeled in this paper. The first is that the borrower may choose between buying a house or renting. Given these alternatives, a contract between a household and a lender makes homeownership feasible and provides insurance to the household against fluctuating rental payments. The second aspect is that, once in a contract, the household may terminate the contract by refinancing the future mortgage and, thus, enter into a new contract. This option will be exercised whenever a combination of house price appreciation and declines in the mortgage rate is sufficient to increase the ex ante expected lifetime utility from the new versus the old contract.

WP 03-04

Importing Technology

Francesco Caselli, *Harvard University*
Daniel Wilson, *FRB San Francisco*

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See p. 63 for the abstract of this paper.

WP 03-05

Inferring Policy Objectives from Economic Outcomes

Richard Dennis, *FRB San Francisco*

This paper stresses that estimated policy rules are reduced-form equations that are silent on many important policy questions. To obtain a structural understanding of monetary policy, it is necessary to estimate the policymaker's objective function rather than its policy reaction function. With these issues in mind, this paper proposes a system-based estimation approach that uses the solution to the policymaker's optimization problem to infer the underlying policy regime from the economy's evolution over time. The paper derives conditions under which the parameters in a policymaker's policy objective function can be identified and estimated. These identification conditions apply to forward-looking rational expectations models as well as to backward-looking models, extending existing results. We apply these conditions to a New Keynesian sticky-price model of the U.S. economy, estimating jointly all of the model's behavioral parameters and the policy regime parameters. The results show that the implicit inflation target and the relative weight placed on interest rate smoothing both declined with Volcker's appointment to Federal Reserve chairman. However, the estimates reveal that other—non-monetary policy—parameters have changed over time also.

WP 03-06

Institutional Efficiency, Monitoring Costs, and the Investment Share of FDI

Joshua Aizenman, *University of California, Santa Cruz*
Mark Spiegel, *FRB San Francisco*

This paper models and tests the implications of institutional efficiency on the pattern of foreign direct investment (FDI). We posit that domestic agents have a comparative advantage over foreign agents in overcoming some of the obstacles associated with corruption and weak institutions. We model these circumstances in a principal-agent framework with costly ex post monitoring and enforcement of an ex ante labor contract. Ex post monitoring and enforcement costs are assumed to be lower for domestic entrepreneurs than for foreign ones, but foreign producers enjoy a countervailing productivity advantage. Under these asymmetries, multinationals pay higher wages than domestic producers, in line with the insight of efficiency wages and with the evidence about the "multinationals wage premium." FDI is also more sensitive to increases in enforcement costs.

We then test this prediction for a cross section of developing countries. We use Mauro's (1995) index of institutional efficiency as an indicator of the strength of property rights enforcement within a given country. We compare institutional efficiency levels for a large cross section of countries in 1989 to subsequent FDI flows from 1990 to 1999. We find that institutional efficiency is positively associated with the ratio of subsequent foreign direct investment flows to both gross fixed capital formation and to private investment. This finding is true for both simple cross sections and for cross sections weighted by country size.

WP 03-07

Currency Boards, Dollarized Liabilities, and Monetary Policy Credibility

Mark Spiegel, *FRB San Francisco*
Diego Valderrama, *FRB San Francisco*

Published in *Journal of International Money and Finance* 22(7) (December) pp. 1,065–1,087.
See p. 60 for the abstract of this paper.

WP 03-08

Military Expenditure, Threats, and Growth

Joshua Aizenman, *University of California, Santa Cruz*
Reuven Glick, *FRB San Francisco*

This paper clarifies one of the puzzling results of the economic growth literature: the impact of military expenditure is frequently found to be nonsignificant or negative, yet most countries spend a large fraction of their GDP on defense and the military. We start by empirical evaluation of the nonlinear interactions between military expenditure, external threats, corruption, and other relevant controls. While growth falls with higher levels of military spending, given the values of the other independent variables, we show that military expenditure in the presence of threats increases growth. We explain the presence of these nonlinearities in an extended version of Barro and Sala-i-Martin (1995), allowing the dependence of growth on the severity of external threats and on the effective military expenditure associated with these threats.

WP 03-09

Endogenous Nontradability and Macroeconomic Implications

Paul R. Bergin, *University of California, Davis*
Reuven Glick, *FRB San Francisco*

This paper proposes a new way of thinking about nontraded goods in an open economy macro model. It develops a simple method for analyzing a continuum of goods with heterogeneous trade costs, and it explores how these costs determine the endogenous decision by a seller of whether to trade a good internationally. This way of thinking is appealing in that it provides a natural explanation for a prominent puzzle in international macroeconomics, that the relative price of nontraded goods tends to move much less volatilely than the real exchange rate. Because nontradedness is an endogenous decision, the good on the margin forms a linkage between the prices of traded and nontraded goods, preventing the two price indexes from wandering too far apart. The paper goes on to find that this mechanism has implications for other macroeconomic issues that rely upon the presence of nontraded goods.

WP 03-10

Robust Monetary Policy with Competing Reference Models

Andrew T. Levin, *Federal Reserve Board*
John C. Williams, *FRB San Francisco*

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See p. 62 for the abstract of this paper.

WP 03-11

Inflation Scares and Forecast-Based Monetary Policy

Athanasios Orphanides, *Federal Reserve Board*
John C. Williams, *FRB San Francisco*

Central banks pay close attention to inflation expectations. In standard models, however, inflation expectations are tied down by the assumption of rational expectations and should be of little independent interest to policymakers. In this paper, we relax the assumption of rational expectations with perfect knowledge and reexamine the role of inflation expectations in the economy and in the conduct of monetary policy. Agents are assumed to have imperfect knowledge of the precise structure of the economy and the policymakers' preferences. Expectations are governed by a perpetual learning technology. With learning, disturbances can give rise to endogenous inflation scares, that is, significant and persistent deviations of inflation expectations from those implied by rational expectations. The presence of learning increases the sensitivity of inflation expectations and the term structure of interest rates to economic shocks, in line with the empirical evidence. We also explore the role of private inflation expectations for the conduct of efficient monetary policy. Under rational expectations, inflation expectations equal a linear combination of macroeconomic variables and, as such, provide no additional information to the policymaker. In contrast, under learning, private inflation expectations follow a time-varying process and provide useful information for the conduct of monetary policy.

WP 03-12

Left Behind: SSI in the Era of Welfare Reform

Mary C. Daly, *FRB San Francisco*
Richard V. Burkhauser, *Cornell University*

Published in *Focus* 22(3) (Summer).
See p. 54 for the abstract of this paper.

WP 03-13

Prices for Local Area Network Equipment

Mark Doms, *FRB San Francisco*
Chris Forman, *Carnegie Mellon University*

In this paper we examine quality-adjusted prices for local area network (LAN) equipment. Hedonic regressions are used to estimate price changes for the two largest classes of LAN equipment, routers and switches. A matched model was used for LAN cards and the prices for hubs were inferred by using an economic relationship to switches. Overall, we find that prices for the four groups of LAN equipment fell at a 17 percent annual rate between 1995 and 2000. These results stand in sharp contrast to the PPI for communications equipment that is nearly flat over the 1990s.

WP 03-14

When Do Matched-Model and Hedonic Techniques Yield Similar Price Measures?

Ana Aizcorbe, *Federal Reserve Board*
Carol Corrado, *Federal Reserve Board*
Mark Doms, *FRB San Francisco*

Hedonic techniques were developed to control for quality differences across goods and over time in order to construct constant-quality aggregate price measures. When the available data are a panel of high-frequency data on models whose characteristics are constant over time, matched-model price indexes can also be used to obtain constant-quality price measures. We show this by demonstrating that, given data of this type, certain matched-model indexes yield price measures that are numerically close to those obtained using hedonic techniques.

WP 03-15

Communications Equipment: What Has Happened to Prices?

Mark Doms, *FRB San Francisco*

Forthcoming in *Measuring Capital in the New Economy.* Chicago: University of Chicago Press.
See p. 55 for the abstract of this paper.

WP 03-16

New Keynesian Optimal-Policy Models: An Empirical Assessment

Richard Dennis, *FRB San Francisco*

This paper estimates two optimization-based sticky-price New Keynesian models and assesses how well they describe U.S. output, inflation, and interest rate dynamics. We consider models in which either internal habit formation or external habit formation influence consumption behavior, and in which Calvo-pricing and inflation indexing generate price and inflation inertia. Subject to constraints dictated by household and firm behavior, monetary policy is set under discretion, and the model's time-consistent equilibrium is employed to estimate key behavioral parameters. We find that specifications estimated on consumption data perform better than specifications estimated on output data and that models with external habit formation outperform models with internal habit formation. Nevertheless, even the best-fitting specification displays characteristics that are inconsistent with the data.

WP 03-17

A Macro-Finance Model of the Term Structure, Monetary Policy, and the Economy

Glenn D. Rudebusch, *FRB San Francisco*
Tao Wu, *FRB San Francisco*

This paper develops and estimates a macro-finance model that combines a canonical affine no-arbitrage finance specification of the term structure with standard macroeconomic aggregate relationships for output and inflation. From this new empirical formulation, we obtain several important results: (1) the latent term structure factors from finance no-arbitrage models appear to have important macroeconomic and monetary policy underpinnings,

(2) there is no evidence of monetary policy inertia or a slow partial adjustment of the policy interest rate by the Federal Reserve, and (3) both forward-looking and backward-looking elements play important roles in macroeconomic dynamics.

WP 03-18

The Macroeconomy and the Yield Curve: A Nonstructural Analysis

Francis X. Diebold, *University of Pennsylvania*
Glenn D. Rudebusch, *FRB San Francisco*
S. Boragan Aruoba, *University of Pennsylvania*

We estimate a model with latent factors that summarize the yield curve (namely, level, slope, and curvature) as well as observable macroeconomic variables (real activity, inflation, and the stance of monetary policy). Our goal is to provide a characterization of the dynamic interactions between the macroeconomy and the yield curve. We find strong evidence of the effects of macro variables on future movements in the yield curve and much weaker evidence for a reverse influence. We also relate our results to a traditional macroeconomic approach based on the expectations hypothesis.

WP 03-19

IT Investment and Firm Performance in U.S. Retail Trade

Mark E. Doms, *FRB San Francisco*
Ron S. Jarmin, *Center for Economic Studies, U.S. Census Bureau*
Shawn D. Klimek, *Center for Economic Studies, U.S. Census Bureau*

We examine the relationship between investments in information technology (IT) and two measures of retail firm performance, labor productivity and productivity growth, over the 1992 to 1997 period. We use untapped firm and establishment micro data from the Censuses of Retail Trade and the Assets and Expenditures Survey. We show that large firms account for most retail IT investment, employment, and establishment growth. We find evidence of a significant relationship between IT investment intensity and productivity growth. We find no evidence of a similar link between IT and growth in the number of establishments operated by retail firms.

WP 03-20

How Fast Do Personal Computers Depreciate? Concepts and New Estimates

Mark E. Doms, *FRB San Francisco*
Wendy E. Dunn, *Federal Reserve Board*
Stephen D. Oliner, *Federal Reserve Board*
Daniel E. Sichel, *Federal Reserve Board*

Forthcoming in *Tax Policy and the Economy,* Volume 18, ed. James Poterba. Cambridge, MA: MIT Press.
See p. 56 for the abstract of this paper.

WP 03-21

The Responses of Wages and Prices to Technology Shocks

Rochelle M. Edge, *Federal Reserve Board*
Thomas Laubach, *Federal Reserve Board*
John C. Williams, *FRB San Francisco*

This paper reexamines wage and price dynamics in response to permanent shocks to productivity. We estimate a micro-founded dynamic general equilibrium model of the U.S. economy with sticky wages and sticky prices using impulse responses to technology and monetary policy shocks. We utilize a flexible specification for wage- and price-setting that allows for the sluggish adjustment of both the levels of these variables—as in standard contracting models—as well as intrinsic inertia in wage and price inflation. On the price front, we find that, in our VAR, inflation jumps in response to an identified permanent technology shock, implying that, on average, prices adjust quickly and that there is little evidence for any intrinsic inflation inertia like that commonly found in models used for monetary policy evaluation. On the wage front, we find evidence for significant inertia in wages and some intrinsic inertia in nominal wage inflation. Our results provide support for the standard sticky-price specification of the New Keynesian model; however, the evidence on the high degree of wage inertia presents a challenge for standard models of wage-setting.

WP 03-22
How Workers Fare When Employers Innovate

Sandra E. Black, *University of California, Los Angeles*
Lisa M. Lynch, *Tufts University*
Anya Krivelyova, *Boston College*

Complementing existing work on firm organizational structure and productivity, this paper examines the impact of organizational change on workers. We find evidence that employers do appear to compensate at least some of their workers for engaging in high performance workplace practices. We also find a significant association between high performance workplace practices and increased wage inequality. Finally, we examine the relationship between organizational structure and employment changes and find that some practices, such as self-managed teams, are associated with greater employment reductions, while other practices, such as the percentage of workers involved in job rotation, are associated with lower employment reductions.

WP 03-23
What's Driving the New Economy? The Benefits of Workplace Innovation

Sandra E. Black, *University of California, Los Angeles*
Lisa M. Lynch, *Tufts University*

This paper argues that changes in workplace organization, including the use of self-managed teams, incentive pay, and employee voice, have been a significant component of the turnaround in productivity growth in the United States during the 1990s. Our work goes beyond measuring the impact of computers on productivity and finds that these types of workplace innovations appear to explain a large part of the movement in multifactor productivity in the United States over the period 1993–1996. These results suggest additional dimensions to the recent productivity growth in the U.S. that may well have implications for productivity growth potential in Europe.

WP 03-24
The Decline of Activist Stabilization Policy: Natural Rate Misperceptions, Learning, and Expectations

Athanasios Orphanides, *Federal Reserve Board*
John C. Williams, *FRB San Francisco*

We develop an estimated model of the U.S. economy in which agents form expectations by continually updating their beliefs regarding the behavior of the economy and monetary policy. We explore the effects of policymakers' misperceptions of the natural rate of unemployment during the late 1960s and 1970s on the formation of expectations and macroeconomic outcomes. We find that the combination of monetary policy directed at tight stabilization of unemployment near its perceived natural rate and large real-time errors in estimates of the natural rate uprooted heretofore quiescent inflation expectations and destabilized the economy. Had monetary policy reacted less aggressively to perceived unemployment gaps, inflation expectations would have remained anchored and the stagflation of the 1970s would have been avoided. Indeed, we find that less activist policies would have been more effective at stabilizing both inflation and unemployment. We argue that policymakers, learning from the experience of the 1970s, eschewed activist policies in favor of policies that concentrated on the achievement of price stability, contributing to the subsequent improvements in macroeconomic performance of the U.S. economy.

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PBWP 03-01

Effectiveness of Official Daily Foreign Exchange Market Intervention Operations in Japan

Rasmus Fatum, *University of Alberta*
Michael Hutchison, *University of California, Santa Cruz*

Japanese official intervention in the foreign exchange market is of by far the largest magnitude in the world, despite little or no evidence that it is effective in moving exchange rates. Up until recently, however, official data on intervention have not been available for Japan. This paper investigates the effectiveness of intervention using recently published official daily data and an event study methodology. The event study fits the stochastic properties of intervention and exchange rate data, i.e., intense and sporadic bursts of intervention activity juxtaposed against a continuously changing yen/dollar rate, better than the standard time-series approaches. Focusing on daily Japanese and U.S. official intervention operations, we identify separate intervention "episodes" and analyze the subsequent effect on the exchange rate. Using the nonparametric sign test and matched sample test, we find strong evidence that sterilized intervention systemically affects the exchange rate in the short run (less than one month). This result holds even when intervention is not associated with (simultaneous) interest rate changes, whether or not intervention is "secret" (in the sense of no official reports or rumors of intervention reported over the news wires), and against other robustness checks. Large-scale interventions (over $1 billion), coordinated with the Bank of Japan and the Federal Reserve working in unison, give the highest success rate. During the period that the Bank of Japan has reduced interbank rates to 0.5 percent and below (from September 1995), however, only one intervention operation has been coordinated with the Fed, and the success rate has been correspondingly low.

PBWP 03-02

Macroeconomic Effects of IMF-Sponsored Programs in Latin America: Output Costs, Program Recidivism, and the Vicious Cycle of Failed Stabilizations

Michael Hutchison, *University of California, Santa Cruz*
Ilan Noy, *University of Hawaii*

We investigate the effects of International Monetary Fund (IMF) stabilization programs and the reasons behind the unusually high IMF activity and relatively low program completion rates in Latin America. We base our tests on a panel and distinguish between IMF program approvals and completion. We find that Latin America has higher output costs of IMF programs (especially when completed), no improvement in the current account, and a much higher likelihood of program failure and recidivism than other regions. The common finding that entering into an IMF-supported program incurs real short-run costs on the economy is driven entirely by the experiences in Latin America.

PBWP 03-03

Determinants of Voluntary Bank Disclosure: Evidence from Japanese Shinkin Banks

Mark Spiegel, *FRB San Francisco*
Nobuyoshi Yamori, *Nagoya University*

Disclosure is widely regarded as a necessary condition for market discipline in a modern financial sector. However, the determinants of disclosure decisions are still unknown, particularly among banks. This paper investigates the determinants of disclosure by Japanese Shinkin banks in 1996 and 1997. This period is unique because disclosure by these banks was voluntary during this time. We find that banks with more serious bad loan problems, more leverage, less competitive pressure, and smaller banks were less likely to choose to disclose voluntarily. These results suggest that there may be a role for compulsory disclosure, as weak banks appear to avoid voluntary disclosure disproportionately.

PBWP 03-04

Gaucho Banking Redux

Gerardo della Paolera, *The American University of Paris*
Alan M. Taylor, *University of California, Davis*

Argentina's economic crisis has strong similarities with previous crises stretching back to the nineteenth century. A common thread runs through all these crises: the interaction of a weak, undisciplined, or corruptible banking sector, and some other group of conspirators from the public or private sector that hastens its collapse. This pampean propensity for crony finance was dubbed "gaucho banking" more than one hundred years ago. What happens when such a rotten structure interacts with a convertibility plan? We compare the 1929 and 2001 crises—the two instances where rigid convertibility plans failed—and reach two main conclusions. First, a seemingly robust currency board can be devastated by an ill-conceived approach to the problems of internal and external convertibility (or, to rephrase Gresham, bad inside money drives out good outside money). Second, when modern economic orthodoxy collides with caudillo-style institutional backwardness, a desperate regime with its hands tied in both monetary and fiscal domains will be sorely tempted by a "capital levy" on the financial sector (for, as Willie Sutton said when asked why he robbed banks, "because that's where the money is").

PBWP 03-05

Crisis Resolution: Next Steps

Barry Eichengreen, *University of California, Berkeley*
Kenneth Kletzer, *University of California, Santa Cruz*
Ashoka Mody, *International Monetary Fund*

At the April 2003 meeting of the International Monetary and Financial Committees, it was decided to further encourage the contractual approach to smoothing the process of sovereign debt restructuring by encouraging the more widespread use of collective action clauses (CACs) in international bonds. This decision was shaped partly by Mexico's successful launch of a bond subject to New York law but featuring CACs, and by subsequent issues with similar provisions from other emerging market countries. This paper reviews the developments leading up to that event, its implications, and prospects for the future. It asks whether we can expect to see additional issuance by emerging markets of bonds featuring CACs, whether such a trend would in fact help to make the world a safer financial place, and what additional steps might be taken to further enhance modalities for crisis resolution.

Abstracts of Articles Accepted in Journals, Books, and Conference Volumes*

Net Foreign Assets and Exchange Rate Dynamics: The Monetary Model Revisited

Michele Cavallo, with
Fabio Ghironi,
Boston College

Forthcoming in *Exchange Rate Dynamics: A New Open Economy Macroeconomics Perspective,* eds. Jean-Olivier Hairault and Thepthida Sopraseuth. London: Routledge, 2004.

We develop a two-country, flexible-price model of exchange rate determination with incomplete asset markets and stationary net foreign assets. We compare exchange rate dynamics in the traditional case of exogenous money supplies and under endogenous interest rate setting. We show that the nominal exchange rate depends on the stock of real net foreign assets in both cases. Thus, shocks that cause holdings of net foreign assets to change generate movements of the exchange rate over time. The exchange rate exhibits a unit root when central banks set interest rates to react to inflation. Endogenous monetary policy and asset dynamics have consequences for exchange rate overshooting. A persistent relative productivity shock results in delayed overshooting. A persistent relative interest rate shock generates undershooting.

Employment Declines among People with Disabilities: Population Movements, Isolated Experience, or Broad Policy Concern?

Mary C. Daly, with
Andrew J. Houtenville,
Cornell University

Published in *The Decline in Employment of People with Disabilities,* eds. D. Stapleton and R. Burkhauser. Kalamazoo, MI: Upjohn, pp. 87–129.

We look beyond the overall decline in employment among working-age people with disabilities in the 1990s to track the importance of three factors on the observed changes: (1) trends among key subgroups, especially those with employment-risk factors other than disability; (2) population shifts towards subgroups with lower-than-average employment rates; and (3) changes in self-reported health status. Our analysis is based on cross-sectional data from the Current Population Survey. Our results suggest that the decline was broad-based, present in a wide range of demographic and educational subgroups. In terms of population shifts, we find no evidence that compositional changes in the population with disabilities account for the average employment decline during the 1990s. In contrast, we find that compositional changes were important to the increase in employment among those with disabilities during the 1980s. Finally, we show that self-reported health among those with disabilities remained relatively stable in the latter half of the 1990s, making changes in health status an unlikely cause of declining employment rates.

*The abstracts are arranged alphabetically by FRB San Francisco authors, whose names are in boldface.

Left Behind: SSI in the Era of Welfare Reform

Mary C. Daly, with
Richard V. Burkhauser,
Cornell University

Published in *Focus* 22(3) (Summer).
http://www.ssc.wisc.edu/irp/focus/foc223.pdf

SSI was established in 1972, born out of a compromise at the time between those wanting to provide a guaranteed income floor and those wishing to limit it to individuals not expected to work: the aged, blind, and disabled. SSI is now the largest federal means-tested program in the United States, serving a population dominated by low-income adults and children with disabilities. With other forms of federal support devolving to state programs (e.g., welfare), policymakers pressing to redefine social expectations about who should and should not work, and the Americans with Disabilities Act guaranteeing people with disabilities the right to employment, the goals and design of SSI have come under scrutiny. In this article we review the role that SSI has played to this point and consider the directions SSI might take in a work-dominated welfare environment where people with disabilities increasingly wish to be included in the labor market.

Economic Outcomes of Working-Age People over the Business Cycle: An Examination of the 1980s and 1990s

Mary C. Daly, with
Richard V. Burkhauser,
Cornell University
Andrew J. Houtenville,
Cornell University
Nigar Nargis,
Cornell University

Forthcoming in
Social Science Quarterly.

We examine the rate of employment and the household income of the working-age population (aged 25–61) with and without disabilities over the business cycles of the 1980s and 1990s using data from the March Current Population Survey and the National Health Interview Survey. In general, we find that while the employment of working-age men and women with and without disabilities exhibited a procyclical trend during the 1980s business cycle, this was not the case during the 1990s expansion. During the 1990s, the employment of working-age men and women without disabilities continued to be procyclical, but the employment rates of their counterparts with disabilities declined over the entire 1990s business cycle. Although increases in disability transfer income replaced a significant fraction of their lost earnings, the household income of men and women with disabilities fell relative to the rest of the population over the decade.

Earnings Mobility and Instability

Mary C. Daly, with
Greg J. Duncan,
Northwestern University

Forthcoming in
Review of Income and Wealth.

We study earnings mobility and instability using data from the Panel Study of Income Dynamics. Our main contribution is to update mobility and instability calculations to include data from the 1990s, although we also provide a number of tests of robustness across mobility and instability indicators and sample definitions. All in all, we find few trends in earnings mobility and instability that persist over the 27-year period we study. As with Gottschalk and Moffitt, we find an increase in earnings instability since the 1970s, particularly among younger workers. However, we find no evidence that instability continued to increase throughout the 1980s and early 1990s. With regard to mobility, we find greater upward mobility and less downward mobility of middle-income workers in the 1980s relative to the 1970s. The former trend appears to have reversed itself by the middle of the 1990s. Employment-based indicators are consistent with the earnings-based indicators in showing increased employment instability between the 1970s and later periods.

Exploring the Role of the Real Exchange Rate in Australian Monetary Policy

Richard Dennis

Published in *The Economic Record* 79(244) pp. 20–38.

An important issue in small open economies is whether policymakers should respond to exchange rate movements when they formulate monetary policy. Microfounded models tend to suggest that there is little to be gained from responding to exchange rate movements, and the literature has largely concluded that such a response is unnecessary, or even undesirable. This paper examines this issue using an estimated model of the Australian economy. In contrast to microfounded models, according to this model policymakers should allow for movements in the real exchange rate and the terms-of-trade when they set interest rates. Further, taking real exchange rate movements into account appears even more important with price level targeting than with inflation targeting.

Solving for Optimal Simple Rules in Rational Expectations Models

Richard Dennis

Published in *Journal of Economic Dynamics and Control* 28(8) (June 2004) pp. 1,635–1,660.

This paper presents algorithms that solve for optimal simple monetary policy rules in rational expectations models with precommitment and discretion. The algorithms are applied to the models in Fuhrer (1997), Clarida et al. (1999), and Rudebusch (2002) to examine the efficiency properties of operational policy rules. We show that optimized Taylor-type rules perform well in these models, but that, aside from the Fuhrer-Moore model, this result is sensitive to whether the central bank can respond to current period shocks. Taylor-type rules that are operational in the sense that they do not respond to current period information are found to be highly inefficient in the Rudebusch model and in the Clarida et al. model.

Communications Equipment: What Has Happened to Prices?

Mark Doms

Forthcoming in *Measuring Capital in the New Economy.* Chicago: University of Chicago Press.

Presented at the Conference on Research in Income and Wealth, NBER, Washington, D.C., April 26–27, 2002.

This paper examines the prices for communications equipment, an important component of information technology. Unlike prices for computers, which officially fall sharply every year, the official prices for communications equipment have barely budged over the past decade. This paper combines earlier work on prices for several segments of communications equipment with new results for public exchanges, fiber-optic equipment, and modems. The results suggest that prices for communications equipment fall much faster than official statistics would indicate, but not as fast as computers. The results presented in this paper, if incorporated into the National Income and Product Accounts, would decrease multifactor productivity growth by about 0.1 percentage point per year and increase the contribution of capital deepening by a like amount. Also, GDP growth would be boosted marginally.

How Fast Do Personal Computers Depreciate? Concepts and New Estimates

Mark Doms, with
Wendy E. Dunn,
Federal Reserve Board of Governors
Stephen D. Oliner,
Federal Reserve Board of Governors
Daniel E. Sichel,
Federal Reserve Board of Governors

Forthcoming in *Tax Policy and the Economy,* Volume 18, ed. James Poterba. Cambridge, MA: MIT Press.

Presented at the NBER Conference on Tax Policy and the Economy, Washington, DC, November 4, 2003.

This paper provides new estimates of depreciation rates for personal computers using an extensive database on prices of used PCs. Our results show that PCs lose roughly half their remaining value, on average, with each additional year of use. We decompose that decline into age-related depreciation and a revaluation effect, where the latter effect is driven by the steep ongoing drop in the constant-quality prices of newly introduced PCs. Our results are directly applicable for measuring the depreciation of PCs in the National Income and Product Accounts (NIPA)—and were incorporated into the December 2003 comprehensive NIPA revision. Regarding tax policy, our estimates suggest that the current tax depreciation schedule for PCs is about right in a zero-inflation environment. However, because the tax code is not indexed for inflation, the tax allowances would be too small in present value for inflation rates above the very low level now prevailing.

Capital Controls and Exchange Rate Instability in Developing Countries

Reuven Glick, with
Michael Hutchison,
University of California, Santa Cruz

Forthcoming in *Journal of International Money and Finance.*

A large literature on the appropriate sequencing of financial liberalization suggests that removing capital controls prematurely may contribute to currency instability. This paper investigates whether legal restrictions on international capital flows are associated with greater currency stability. We employ a comprehensive panel data set of 69 developing economies over the 1975–1997 period, identifying 160 currency crises. We control for macroeconomic, political, and institutional characteristics that influence the probability of a currency crisis, employ alternative measures of restrictions on international payments, and account for possible joint causality between the likelihood of a currency attack and the imposition of capital controls. We find evidence that restrictions on capital flows do not effectively insulate economies from currency problems; rather, countries with less restrictive capital controls and more liberalized regimes appear to be less prone to speculative attacks.

Incorporating Equity Market Information into Supervisory Monitoring Models

John Krainer
Jose A. Lopez

Forthcoming in *Journal of Money, Credit, and Banking.*

We examine whether equity market variables, such as stock returns and equity-based default probabilities, are useful to U.S. bank supervisors for assessing the condition of domestic bank holding companies. We develop a model of supervisory ratings that easily combines supervisory and equity market information. We find that the model's forecasts anticipate supervisory ratings changes by up to four quarters. Relative to simply using supervisory variables, the inclusion of equity market variables in the model does not improve forecast accuracy. However, we argue that equity market information should still be useful for forecasting supervisory ratings and should be incorporated into supervisory monitoring models.

Forecasting Bank Supervisory Ratings Using Securities Market Information

John Krainer
Jose A. Lopez

Forthcoming in *FRB Chicago Bank Structure and Competition Conference Proceedings.*

Approximately once a year, bank supervisors in the United States conduct a comprehensive on-site inspection of a bank holding company and assign it a supervisory rating meant to summarize its overall condition. We develop an empirical forecasting model of these ratings that combines accounting and financial market data. We find that securities market variables, such as stock returns and changes in bond yield spreads, improve the model's in-sample fit. Both equity and debt market variables appear to be useful for explaining upgrades and downgrades. We conclude that stock and bond market investors possess different but complementary information about bank holding company condition. In an out-of-sample forecasting exercise, we find that the forecast accuracy of the model with both equity and debt variables is little different from the accuracy of a model based on accounting and lagged supervisory data alone.

Impact of Deposit Rate Deregulation in Hong Kong on the Market Value of Commercial Banks

Simon Kwan

Published in *Journal of Banking and Finance* 27(12) (December) pp. 2,231–2,248.

This paper examines the effects of a series of events leading up to the deregulation of deposit interest rates in Hong Kong on the market value of banks. All the evidence suggests that banks earned rents from deposit interest rate rules, and deregulation would lower these rents and hence bank market values. On average, the total abnormal return due to interest rate deregulation was around negative 4 percent. There is some evidence that large banks and banks with high deposit-to-asset ratios suffered a bigger drop in value, suggesting that these banks enjoyed a bigger subsidy under the interest rate rules.

Operating Performance of Banks among Asian Economies: An International and Time Series Comparison

Simon Kwan

Published in *Journal of Banking and Finance* 27(3) (March) pp. 471–489.

Per unit bank operating costs are found to vary significantly across Asian countries and over time. The strong correlation between per unit labor cost and physical capital cost suggests that there exist systematic differences in bank operating efficiency across countries. The declining operating costs between 1992 and 1997 are consistent with improving operating performance. Since 1997, the run-up in operating costs coincided with the Asian financial crisis, suggesting that banks incurred additional costs to deal with problem loans while outputs declined simultaneously. Labor cost share is also found to decline significantly between 1997 and 1999, perhaps because banks were able to cut labor force faster than physical capital. Significant differences in labor cost share across countries suggest cross-country differences in bank production functions. The positive relation between labor cost share and wage rate indicates that banks using more labor is due to labor force productivity, rather than labor being cheap.

Market Evidence on the Opaqueness of Banking Firms' Assets

Simon Kwan, with
Mark J. Flannery,
University of Florida, Gainesville
M. Nimalendran,
University of Florida, Gainesville

Published in *Journal of Financial Economics* 71(3) (March 2004) pp. 419–460.

We assess the market microstructure properties of U.S. banking firms' equity to determine whether they exhibit more or less evidence of asset opaqueness than similar-sized nonbanking firms. The evidence indicates that large bank holding companies (BHCs), traded on the NYSE, have very similar trading properties to their matched nonfinancial firms. In contrast, smaller BHCs, traded on NASDAQ, trade much less frequently despite having very similar spreads. Analysis of IBES earnings forecasts indicates that banking assets are not unusually opaque; they are simply boring. The implications for regulatory policy and future market microstructure research are discussed.

Forward-Looking Behavior and Optimal Discretionary Monetary Policy

Kevin Lansing
Bharat Trehan

Published in *Economics Letters* 81(2) (November) pp. 249–256.

This paper derives a closed-form solution for the optimal discretionary monetary policy in a small macroeconomic model that allows for varying degrees of forward-looking behavior. We show that a more forward-looking aggregate demand equation serves to attenuate the response to inflation and the output gap in the optimal interest rate rule. In contrast, a more forward-looking real interest rate equation serves to magnify the response to both variables. A more forward-looking Phillips curve serves to attenuate the response to inflation but magnify the response to the output gap. The results have implications for studies that attempt to reconcile estimated versions of the central bank's policy rule with optimal discretionary monetary policy. In particular, a successful reconciliation is likely to require a different degree of forward-looking behavior in each part of the model economy.

Growth Effects of Shifting from a Graduated-Rate Tax System to a Flat Tax

Kevin Lansing, with
Steven P. Cassou,
Kansas State University

Published in *Economic Inquiry* 42(2) (April 2004) pp. 194–213.

This paper develops a quantitative general equilibrium model to assess the growth effects of adopting a flat tax plan similar to the one proposed by Hall and Rabushka (1995). Using parameters calibrated to match the level and slope of the U.S. tax schedule and other features of the U.S. economy, we compute the growth effects of adopting a revenue-neutral flat tax for both a human-capital based endogenous growth model and a standard neoclassical growth model. For the endogenous-growth version of the model, long-run growth effects are decomposed into the parts attributable to the flattening of the marginal tax schedule, the full expensing of physical-capital investment, and the elimination of double taxation of business income. We find that the most important element of the reform is the flattening of the marginal tax schedule. Without this element, the combined effects of the other parts of the reform can actually reduce long-run growth. For the neoclassical growth model, we find that the transition dynamics following the adoption of a flat tax can be quite lengthy. In the years immediately following the reform, the economy's output trajectory is quite similar to that of the endogenous growth model. In both versions of the model, shifting to a flat tax initially produces a growth slowdown due to the higher post-reform tax rate that is

needed to maintain revenue neutrality. After about six years, the additional capital accumulation induced by changes in the tax code allows the post-reform output trajectory to overtake the pre-reform trend.

Globally Stabilizing Fiscal Policy Rules

Kevin Lansing, with
Jang-Ting Guo,
University of California, Riverside

Published in *Studies in Nonlinear Dynamics and Econometrics* 7(2).

This paper demonstrates how fiscal policy rules can be designed to eliminate all forms of endogenous fluctuations in a one-sector growth model with increasing returns-to-scale. When the policy rules are implemented, agents' optimal decisions depend only on the current state of the economy and not on any expected future states. This property shuts down the mechanism for expectations-driven fluctuations. The proposed policy rules ensure a globally unique and stable equilibrium, regardless of the degree of increasing returns.

The Empirical Relationship between Average Asset Correlation, Firm Probability of Default, and Asset Size

Jose A. Lopez

Forthcoming in *Journal of Financial Intermediation.*

The asymptotic single risk factor approach is a framework for determining regulatory capital charges for credit risk, and it has become an integral part of the second Basel Accord. Within this approach, a key parameter is the average asset correlation. We examine the empirical relationship between this parameter and firm probability of default and firm asset size measured by the book value of assets. Using data from year-end 2000, credit portfolios consisting of U.S., Japanese, and European firms are analyzed. The empirical results suggest that average asset correlation is a decreasing function of probability of default and an increasing function of asset size. The results suggest that these factors may need to be accounted for in the final calculation of regulatory capital requirements for credit risk.

Formulating the Imputed Cost of Equity Capital for Priced Services at Federal Reserve Banks

Jose A. Lopez, with
Edward J. Green, *FRB Chicago*
Zhenyu Wang, *Columbia University*

Published in *FRB New York Economic Policy Review* 9(3) (September) pp. 55–81.

According to the 1980 Monetary Control Act, the Federal Reserve Banks must establish fees for their priced services to recover all operating costs as well as the imputed costs of capital and taxes that would be incurred by a profit-making firm. Since 2002, the Federal Reserve has made fundamental changes to the calculations used to set the imputed costs. This article describes and analyzes the current approach, which is based on a simple average of three methods as applied to a peer group of bank holding companies. The methods estimate the cost of equity capital from three perspectives—the historical average of comparable accounting earnings, the discounted value of expected future cash flows, and the equilibrium price of investment risk as per the capital asset pricing model. The authors show that the current approach also provides stable and sensible estimates of the cost of equity capital over the past 20 years.

Assessing the Lucas Critique in Monetary Policy Models

Glenn Rudebusch

Forthcoming in *Journal of Money, Credit, and Banking.*

Empirical estimates of monetary policy rules suggest that the behavior of U.S. monetary policymakers changed during the past few decades. However, for that same time period, statistical analyses of lagged representations of the economy, such as VARs, often have not rejected the null of structural stability. These two sets of empirical results appear to contradict the Lucas critique. This paper reconciles these results with the Lucas critique by showing that the apparent policy invariance of reduced forms is consistent with the magnitude of historical policy shifts and the relative insensitivity of the reduced forms of plausible forward-looking macroeconomic specifications to policy shifts.

Estimating the Euler Equation for Output

Glenn Rudebusch, with
Jeffrey Fuhrer, *FRB Boston*

Forthcoming in *Journal of Monetary Economics.*

New Keynesian macroeconomic models have generally emphasized that expectations of future output are a key factor in determining current output. The theoretical motivation for such forward-looking behavior relies on a straightforward generalization of the well-known Euler equation for consumption. In this paper, we use maximum likelihood and generalized method of moments (GMM) methods to explore the empirical importance of output expectations. We find little evidence that rational expectations of future output help determine current output, especially after taking into account the small-sample bias in GMM.

Currency Boards, Dollarized Liabilities, and Monetary Policy Credibility

Mark Spiegel
Diego Valderrama

Published in *Journal of International Money and Finance* 22(7) (December) pp. 1,065–1,087.

The recent collapse of the Argentine currency board raises new questions about the desirability of formal fixed exchange rate regimes. This paper examines the relative performance of a currency board with costly abandonment in the presence of dollarized liabilities to a fully discretionary regime. Our results demonstrate that neither regime necessarily dominates with only idiosyncratic firm shocks, but discretion unambiguously dominates with the addition of shocks to the dollar–euro rate. The relatively strong performance of the discretionary regime in this model stems from the benign impact of dollarized liabilities on the monetary authority's time-inconsistency problem.

Sterilization Costs and Exchange Rate Targeting

Mark Spiegel, with
Kenneth Kletzer,
University of California, Santa Cruz

Forthcoming in *Journal of International Money and Finance.*

We examine the movements of exchange rates and capital inflows in an environment where an optimizing central bank pursuing the joint goals of inflation and output targeting engages in costly sterilization activities. Our results predict that, when faced with increased sterilization costs, the central bank will choose to limit its sterilization activities, allowing target variables, such as the nominal exchange rate, to adjust. We then test the predictions of a linearized version of the saddle-path solution to the model for a cross-country panel of developing countries. We use OLS, IV, and GMM specifications to allow for the endogeneity of capital inflows. Our results confirm that monetary policy does respond to sterilization costs.

The Impact of Japan's Financial Stabilization Laws on Bank Equity Values

Mark Spiegel, with
Nobuyoshi Yamori, *Nagoya University*

Published in *Journal of the Japanese and International Economies* 17(3) (September) pp. 263–282.

In the fall of 1998, two important financial regulatory reform acts were passed in Japan. The Financial Reconstruction Act created a bridge bank scheme and provided funds for the resolution of failed banks. The Rapid Recapitalization Act provided funds for the assistance of troubled banks. These acts provided government assistance to the banking sector and called for reforms aimed at strengthening the regulatory environment. Using an event study framework, we examine the anticipated impact of these regulatory reforms. Our evidence suggests that the Financial Reconstruction Act was expected to hurt large banks, while the anticipated impact of the act by financial strength was mixed. In contrast, the anticipated impact of the Rapid Recapitalization Act was expected to be anti-reform, as news favorable to its passage disproportionately favored large and weak Japanese banks.

Financial Turbulence and the Japanese Main Bank Relationship

Mark Spiegel, with
Nobuyoshi Yamori, *Nagoya University*

Published in *Journal of Financial Services Research* 23(3) (June) pp. 205–223.

Under the Japanese "main bank" relationship, a bank holds equity in a firm and plays a leading role in its decisionmaking and financing. This may leave a firm dependent on its main bank for financing due to its information advantage over other potential lenders. This dependency may be particularly severe during episodes of financial turbulence. We examine the sensitivity of returns on portfolios of Japanese firm equity to the returns of their main banks using a three-factor arbitrage-pricing model. We find no significant dependence when coefficient values are held constant over the entire sample. However, the data strongly suggest a structural break in the relationship subsequent to the last quarter of 1997, a turbulent period for Japanese financial markets. When a structural break is introduced, main bank sensitivity increases after the break, usually to significantly positive levels.

Measuring the Natural Rate of Interest

John C. Williams, with
Thomas Laubach,
Federal Reserve Board of Governors

Published in *Review of Economics and Statistics* 85(4) (November) pp. 1,063–1,070.

The natural rate of interest—the real interest rate consistent with output equaling its natural rate and stable inflation—plays a central role in macroeconomic theory and monetary policy. Estimation of the natural rate of interest, however, has received little attention. We apply the Kalman filter to estimate jointly time-varying natural rates of interest and output and trend growth. We find a close link between the natural rate of interest and the trend growth rate, as predicted by theory. Estimates of the natural rate of interest, however, are very imprecise and subject to considerable real-time measurement error.

The Performance of Forecast-Based Monetary Policy Rules under Model Uncertainty

John C. Williams, with
Andrew Levin,
Federal Reserve Board of Governors
Volker Wieland,
Goethe University

Published in *American Economic Review* 93(3) (June) pp. 622–645.

We investigate the performance of forecast-based monetary policy rules using five macroeconomic models that reflect a wide range of views on aggregate dynamics. We identify the key characteristics of rules that are robust to model uncertainty; such rules respond to the one-year-ahead inflation forecast and to the current output gap and incorporate a substantial degree of policy inertia. In contrast, rules with longer forecast horizons are less robust and are prone to generating indeterminacy. Finally, we identify a robust benchmark rule that performs very well in all five models over a wide range of policy preferences.

Robust Monetary Policy with Competing Reference Models

John C. Williams, with
Andrew T. Levin,
Federal Reserve Board of Governors

Published in *Journal of Monetary Economics* 50(5) (July) pp. 945–975.

The existing literature on robust monetary policy rules has largely focused on the case in which the policymaker has a single reference model while the true economy lies within a specified neighborhood of the reference model. In this paper, we show that such rules may perform very poorly in the more general case in which non-nested models represent competing perspectives about controversial issues such as expectations formation and inflation persistence. Using Bayesian and minimax strategies, we then consider whether any simple rule can provide robust performance across such divergent representations of the economy. We find that a robust outcome is attainable only in cases where the objective function places substantial weight on stabilizing both output and inflation; in contrast, we are unable to find a robust policy rule when the sole policy objective is to stabilize inflation. We analyze these results using a new diagnostic approach, namely, by quantifying the fault tolerance of each model economy with respect to deviations from optimal policy.

Embodying Embodiment in a Structural, Macroeconomic Input-Output Model

Daniel J. Wilson

Published in
Economic Systems Research 15(3)
(September) pp. 371–398.

In this paper, I develop a regression-based system of labor productivity equations that account for capital-embodied technological change, and I incorporate this system into IDLIFT, a structural, macroeconomic input-output model of the U.S. economy. Builders of regression-based forecasting models have long had difficulty finding labor productivity equations that exhibit the "Solowian" property that movements in investment should cause accompanying movements in labor productivity. The production theory developed by Solow and others dictates that this causation is driven by the effect of traditional capital deepening as well as technological change embodied in capital. Lack of measurement of the latter has hampered the ability of researchers to estimate properly the productivity-investment relationship. Recent research by Wilson (2001) has alleviated this difficulty by estimating industry-level embodied technological change. In this paper, I utilize those estimates to construct capital stocks adjusted for technological change and then use these adjusted stocks to estimate Solow-type labor productivity equations. It is shown that replacing IDLIFT's former productivity equations, based on changes in output and time trends, with the new equations, results in a convergence between the dynamic behavior of the model and that predicted by traditional (Solowian) production theory.

Importing Technology

Daniel J. Wilson, with
Francesco Caselli,
Harvard University

Published in *Journal of Monetary Economics* 51(1) (January 2004) pp. 1–32.
Prepared for April 2003 Carnegie-Rochester Conference on Public Policy.

We look at disaggregated imports of various types of equipment to make inferences on cross-country differences in the composition of equipment investment. We make three contributions. First, we document large differences in investment composition. Second, we explain these differences as being based on each equipment type's intrinsic efficiency, as well as on its degree of complementarity with other factors whose abundance differ across countries. Third, we examine the implications of investment composition for development accounting, i.e., for explaining the cross-country variation in income per capita.

Quantifying Embodied Technological Change

Daniel J. Wilson, with
Plutarchos Sakellaris,
University of Maryland

Published in *Review of Economic Dynamics* 7(1) (January) pp. 1–26.

We estimate the rate of embodied technological change directly from plant-level manufacturing data on current output and input choices along with histories on their vintages of equipment investment. Our estimates range between 8 percent and 17 percent for the typical U.S. manufacturing plant during the years 1972–1996. Any number in this range is substantially larger than is conventionally accepted with some important implications. First, the role of investment-specific technological change as an engine of growth is even larger than previously estimated. Second, existing producer durable price indexes do not adequately account for quality change. As a result, measured capital stock growth is biased. Third, if accurate, the Hulten and Wykoff (1981) economic depreciation rates may primarily reflect obsolescence.

Stylized Facts on Nominal Term Structure and Business Cycles: An Empirical VAR Study

Tao Wu

Published in *Applied Economics* 35(8) (May 20) pp. 901–906.

This paper examines the importance of various macroeconomic shocks in explaining the movement of the term structure of nominal bond yields in the post-war U.S., as well as the channels through which such macro shocks influence the yield curve, using a structural vector autoregressive model. The results show that the monetary policy and the aggregate supply shocks are important determinants of the nominal term structure. Moreover, the monetary policy innovations have a large but transitory effect on the nominal bond yields, primarily by changing the slope of the yield curve, and the aggregate supply shocks from the private sector have a more persistent effect on the level of the yield curve but have little effect on the slope of the yield curve.

Conferences

Finance and Macroeconomics

Technology, Productivity, and Public Policy

The San Francisco Fed's Research Department organized two conferences in 2003.

The first, cohosted with the Stanford Institute for Economic Policy Research, explored the relationship between macroeconomic fundamentals and the term structure of interest rates and financial asset valuations. Participants discussed the fundamental determinants of equity prices and exchange rates, looked at how policy surprises and "news" affect the equity premium and long-term bond rates, respectively, and considered how policy shocks can be transmitted when short-term interest rates are at zero.

The second conference was the inaugural event of the Department's new Center for the Study of Innovation and Productivity (CSIP). The conference included papers on a broad range of topics written by economists in microeconomics, macroeconomics, and international economics. Conference topics included measuring trend productivity growth and modeling production technologies. Papers also addressed technological diffusion, intellectual property rights, incentives to innovate, and differentials in productivity across countries and individuals.

These conferences bring professional economists from the Federal Reserve System and from research institutions together with policymakers from the U.S. and abroad. Many of the papers presented are "works in progress" and therefore represent the latest research on policy-related issues.

Attendance at all of the conferences is by invitation only. In addition, the papers are chosen from submissions by a select group of noted researchers.

In this section are the conference agendas as well as summaries of the conferences that appeared in our *FRBSF Economic Letter*.

Finance and Macroeconomics

Federal Reserve Bank of San Francisco
February 28 to March 1, 2003

Cosponsored by the Federal Reserve Bank of San Francisco and the Stanford Institute for Economic Policy Research

Papers presented at this conference can be found on the conference website
http://www.frbsf.org/economics/conferences/0303/index.html

Keynote Speaker	Don Kohn, *Federal Reserve Board of Governors*
Dynamics of Corporate Earnings	Robert E. Hall, *Stanford University* Discussant: Andrew Abel, *University of Pennsylvania*
What Explains the Stock Market's Reaction to Federal Reserve Policy?	Ben Bernanke, *Federal Reserve Board of Governors* Kenneth N. Kuttner, *FRB New York* Discussant: Christopher Sims, *Princeton University*
The Case for Open-Market Purchases in a Liquidity Trap	Alan Auerbach, *University of California, Berkeley* Maurice Obstfeld, *University of California, Berkeley* Discussant: Lars Svensson, *Princeton University*
What Does the Yield Curve Tell Us about GDP Growth?	Andrew Ang, *Columbia University* Monika Piazzesi, *University of California, Los Angeles* Min Wei, *Columbia University* Discussant: Mark Watson, *Princeton University*
A Joint Econometric Model of Macroeconomic and Term Structure Dynamics	Peter Hördahl, *European Central Bank* Oreste Tristani, *European Central Bank* David Vestin, *European Central Bank* Discussant: Ken Singleton, *Stanford University*
Exchange Rates and Fundamentals	Charles Engel, *University of Wisconsin* Kenneth D. West, *University of Wisconsin* Discussant: Clive Granger, *University of California, San Diego*
The Excess Sensitivity of Long-Term Interest Rates: Evidence and Implications for Macroeconomic Models	Refet Gürkaynak, *Federal Reserve Board of Governors* Brian Sack, *Federal Reserve Board of Governors* Eric Swanson, *Federal Reserve Board of Governors* Discussant: Qiang Dai, *New York University*

Technology, Productivity, and Public Policy

Federal Reserve Bank of San Francisco
November 7–8, 2003

Sponsored by the Center for the Study of Innovation and Productivity, Federal Reserve Bank of San Francisco

Papers presented at this conference can be found on the conference website
http://www.frbsf.org/economics/conferences/0311/index.html

Keynote Speaker	Martin Baily, *Institute for International Economics*
Tracking the New Economy: Using Growth Theory to Detect Changes in Trend Productivity	James Kahn, *FRB New York* Robert Rich, *FRB New York* Discussants: Robert Gordon, *Northwestern University* James Hamilton, *University of California, San Diego*
Growth, Capital Shares, and a New Perspective on Production Functions	Charles I. Jones, *University of California, Berkeley* Discussants: Sam Kortum, *University of Minnesota* Susanto Basu, *University of Michigan*
Frictionless Technology Diffusion: The Case of Tractors	Rodolfo Manuelli, *University of Wisconsin, Madison* Ananth Seshadri, *University of Wisconsin, Madison* Discussants: William White, *Research Triangle Institute* Bart Hobijn, *FRB New York*
The Political Economy of Intellectual Property Treaties	Suzanne Scotchmer, *University of California, Berkeley* Discussants: Hal Varian, *University of California, Berkeley* Jenny Lanjouw, *University of California, Berkeley*
Incentives and Invention in Universities	Saul Lach, *The Hebrew University* Mark Schankerman, *London School of Economics* Discussants: James Adams, *Rennselaer Polytechnic Institute* Bronwyn Hall, *University of California, Berkeley*
Relative Prices and Relative Prosperity	Chang-Tai Hsieh, *University of California, Berkeley* Peter Klenow, *Stanford University* Discussants: Francesco Caselli, *Harvard University* Mark Spiegel, *FRB San Francisco*
The Skill Content of Recent Technological Change: An Empirical Exploration	David Autor, *Massachusetts Institute of Technology* Frank Levy, *Massachusetts Institute of Technology* Richard Murnane, *Harvard University* Discussants: David Card, *University of California, Berkeley* Kathryn Shaw, *Stanford University*

Finance and Macroeconomics

Federal Reserve Bank of San Francisco
February 28 – March 1, 2003

Reprinted from FRBSF Economic Letter *2003-12, May 2, 2003.*

This *Economic Letter* summarizes papers presented at the conference "Finance and Macroeconomics" held at the Federal Reserve Bank of San Francisco on February 28 and March 1, 2003, under the joint sponsorship of the Bank and the Stanford Institute for Economic Policy Research.

The finance literature and the macroeconomics literature often approach the same economic topic from different perspectives and with different techniques. The seven papers presented at this conference provide some exciting new research at the confluence of these two disciplines.

Three of the papers examine the relationship between financial asset valuations and macroeconomic fundamentals. Hall tries to account for corporate equity valuations using fundamentals such as taxes, risk, and depreciation with mixed results. Bernanke and Kuttner also examine the fundamental determinants of equity prices, but they focus only on monetary policy surprises, which appear to have a significant effect through changes in the equity premium. Engel and West try to pin down whether exchange rates, when viewed as asset prices, can be related to fundamentals.

Three papers consider the interaction between the term structure of interest rates and macroeconomic fundamentals. Ang, Piazzesi, and Wei simplify the entire yield curve to just two factors—the general level of interest rates and the slope or tilt of the yield curve—and then model these two factors along with real GDP growth. Hördahl, Tristani, and Vestin examine a similar structure with a more detailed accounting for macroeconomic dynamics that relates movements in bond yields to shocks in demand, supply, monetary policy, and an inflation target. Gürkaynak, Sack, and Swanson focus on the excess sensitivity of long-term rates to economic news. All three papers emphasize changes in the general level of interest rates, which they interpret as time variation in inflation or in the inflation target.

Auerbach and Obstfeld suggest an important role for the transmission of expansionary monetary policy through quantities when short-term interest rates are at zero. Such a situation typically is not addressed by the standard analyses in finance or macroeconomics, which focus on allocation by price using linear models.

Dynamics of corporate earnings

Hall investigates why the market value of corporate claims in the late 1990s was so high relative to the book value of the sector's capital stock. However, rather than focus on the market value relative to capital's replacement cost, his study looks at corporate earnings and what they add to a company's value. To assess a company's corporate earnings, he develops a theoretical benchmark that includes adjustments to account for the cost of supplying capital services, of risk, and of capital adjustment.

He finds that, at the company level, actual earnings are broadly consistent with the theoretical benchmark, indicating that taxes, depreciation, risk, and adjustment costs account for most of the observed movements in earnings, leaving little room for earnings on intangibles to explain market values. At the industry level, in contrast, he finds substantial discrepancies between earnings and the theoretical benchmark. However, these discrepancies do not appear to be caused by rents associated with adjustment costs. In resource-based industries, these discrepancies can be accounted for by fluctuations in the value of extracted resources, while in the auto industry they are partly accounted for by the decline in domestic production in the early 1980s, caused by high gas prices and increased competition with Japan.

Stock market reactions to Federal Reserve policy

Bernanke and Kuttner quantify the stock market's response to surprise monetary policy interventions and assess the reasons for the response. They use the movements in federal funds rate futures that occur on the day of a change in the target policy rate to obtain a market-based measure of the surprise component of the policy intervention. (Rudebusch (1998) provides a discussion of such market-based measures.) The authors then analyze the stock market's response to the sequence of unanticipated changes in the funds rate.

Their results show that the stock market responds strongly to surprise changes in the federal funds rate. On average, the S&P 500 rises about 1.3 percent for every 25-

basis-point surprise policy easing. However, some industries respond more than others; the construction sector shows the largest response, while the mining and utility sectors register almost no response. The markets do not respond in any significant way to the anticipated component of policy interventions. The results show that an unanticipated policy easing causes an immediate increase in equity prices, but that this increase is then followed by a sustained period of lower-than-normal returns. One way to interpret this result is that financial markets correlate monetary policy surprises with changes in the equity premium.

The yield curve and GDP growth

Ang, Piazzesi, and Wei build a model that uses features of the term structure of interest rates to forecast movements in real GDP growth. In principle, a steep yield curve should signal rising growth rates. However, because interest rates tend to be highly correlated with one another, making it difficult to disentangle which, if any, aspect of the yield curve offers explanatory power, the authors' solution is to condense the information in the term structure into a small number of variables, or factors. The factors used are the level of the nominal interest rate, the slope of the interest rate term structure, and lagged real GDP growth.

They use three methods to determine whether these factors help forecast real GDP growth. The first method regresses future economic growth on the factors, without modeling the factors themselves. The second models the factors using an unrestricted vector autoregression (VAR) and uses the predictions from it to forecast future real growth. The third method is closely related to the second, in that a VAR is used to model the factors, but now no-arbitrage restrictions are imposed, giving the system greater structure.

The authors find that, regardless of the forecast horizon for economic growth, the slope of the term structure should use the difference between the longest and the shortest possible bond yields. They also find that imposing the no-arbitrage conditions on the VAR when modeling the factors leads to better predictive power than an unrestricted VAR. Surprisingly, however, it is the level of the term structure rather than its slope that provides the predictive power. Moreover, it is the inflation component of the nominal interest rate, rather than the real interest rate component, that helps forecast future economic growth.

Macroeconomic and term structure dynamics

Hördahl, Tristani, and Vestin estimate a joint model of macroeconomic and yield curve dynamics. When this model is solved, bond yields are linearly related to macroeconomic fundamentals, whose evolution over time determines how bond yields and the slope and curvature of the term structure respond to shocks and to macroeconomic developments. The absence of arbitrage opportunities is imposed and the resulting model provides a relatively good description of German data, while accommodating demand shocks, supply shocks, monetary policy shocks, and an inflation target shock.

The model estimates reveal several interesting results. Notably, the inflation target for Germany is found to have declined from around 4 percent in 1975 to around 1 percent in 1998. The model predicts that a shock to the inflation target leads to gradual increases in inflation and output and pushes up the middle portion of the yield curve more than either the short or long ends of the curve. Monetary policy shocks tend to reduce output with little impact on prices and cause the yield curve to flatten, although this latter effect dissipates after four to five years. The model also implies that an increase in the inflation target will lead to a large increase in the term premia; however, the term premia are relatively well insulated from other macroeconomic shocks.

Exchange rates and fundamentals

Engel and West examine how exchange rate movements are related to fundamentals. Ever since Meese and Rogoff (1983) showed that uncovered interest parity, the hypothesis that expected exchange rate movements are related to interest rate differentials, was unable to forecast exchange rate movements better than the assumption that the exchange rate follows a random walk, modeling exchange rates has been troublesome. However, instead of examining how exchange rate changes relate to fundamentals, such as interest rate differentials, they examine how future fundamentals relate to past exchange rate changes. Central to this approach is the notion that exchange rates are asset prices that depend on expectations. If exchange rates reflect expected future fundamentals, then, from a statistical standpoint, changes to the exchange rate should help forecast, or "cause," future movements in fundamentals.

Engel and West consider several candidates for exchange rate fundamentals including relative money supplies, relative price levels, interest rate differentials, and relative income. They test whether changes in these fundamentals are predicted by changes in bilateral exchange rates, using data for the U.S. and the remaining six G-7 countries. They find causality from exchange rates to fundamentals in 12 out of 36 cases, while they find causality in the opposite direction in only 2 out of 36 cases. For the post-1990 period, the results are more balanced, with causality from exchange rate to fundamentals found in 14 out of 36 cases and causality from fundamentals to exchange rates obtained in 10 out of 36 cases. These results provide a bit more support than most other studies for the view that exchange rate movements are related to fundamentals.

Excess sensitivity of long-term interest rates

Gürkaynak, Sack, and Swanson examine why long-term interest rates are as sensitive as short-term rates to news and data releases that are expected to have only temporary implications for the economy. Standard term-structure models hold that long-term interest rates should be closely related to an average of expected future short-term interest rates and that, due to this averaging effect, news about the cyclical dynamics of the economy should affect short-term interest rates much more than long-term interest rates.

After examining several explanations for this "interest rate sensitivity" puzzle, the authors conclude that uncertainty about the Federal Reserve's implicit inflation target is the source of this sensitivity. This uncertainty leaves investors unsure of how the Federal Reserve will respond to news; in particular, economic news could alter the inflation target and have a sustained impact on long-run inflation expectations. Such movements in long-run inflation expectations would then be reflected in long-term interest rates.

Open market purchases in a liquidity trap

Auerbach and Obstfeld examine whether monetary policy is effective when short-term nominal interest rates are zero, i.e., when the economy is in a liquidity trap. A liquidity trap is widely seen as problematic because it makes the standard method for easing policy—cutting short-term rates—impossible. The authors argue that monetary policy interventions in the form of expansionary open market operations can still stimulate the economy and raise welfare even during a liquidity trap because they monetize part of the national debt and because they create the expectation that prices will rise.

The advantage to monetizing part of the national debt is that it allows the government to cut other tax rates, reducing distortions, without adversely affecting the government's balance sheet. The benefit to creating the expectation that prices will rise is that it generates an immediate increase in today's price level while also boosting current output levels. The authors show that a 1 percent increase in the level of base money could lead to a permanent annual welfare gain of about 0.06 percent of national income. Applying their findings to Japan, which many believe is stuck in a liquidity trap, the authors argue that although the Bank of Japan's interventions have had no apparent impact on inflation, they have, nevertheless, raised welfare.

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Glenn D. Rudebusch
Vice President

Conference Papers

Papers are available in pdf format at http://www.frbsf.org/economics/conferences/0303/index.html

Ang, Andrew, Monika Piazzesi, and Min Wei. "What Does the Yield Curve Tell Us about GDP Growth?" Columbia Business School.

Auerbach, Alan J., and Maurice Obstfeld. "The Case for Open-Market Purchases in a Liquidity Trap." University of California, Berkeley.

Bernanke, Ben S., and Kenneth N. Kuttner. "What Explains the Stock Market's Reaction to Federal Reserve Policy?" Board of Governors of the Federal Reserve System.

Engel, Charles, and Kenneth D. West. "Exchange Rate and Fundamentals." University of Wisconsin.

Gürkaynak, Refet, Brian Sack, and Eric Swanson. "The Excess Sensitivity of Long-Term Interest Rates: Evidence and Implications for Macroeconomic Models." Board of Governors of the Federal Reserve System.

Hall, Robert. "Dynamics of Corporate Earnings." Stanford University.

Hördahl, Peter, Oreste Tristani, and David Vestin. "A Joint Econometric Model of Macroeconomic and Term Structure Dynamics." European Central Bank.

References

Meese, Richard, and Kenneth Rogoff. 1983. "Empirical Exchange Rate Models of the Seventies: Do They Fit out of Sample?" *Journal of International Economics* 14, pp. 3–24.

Rudebusch, Glenn. 1998. "Do Measures of Monetary Policy in a VAR Make Sense?" *International Economic Review* 39, pp. 907–931.

Technology, Productivity, and Public Policy

Federal Reserve Bank of San Francisco
November 7–8, 2003

Reprinted from FRBSF Economic Letter *2004-07, March 12, 2004*

This *Economic Letter* summarizes papers presented at the conference "Technology, Productivity, and Public Policy" held at the Federal Reserve Bank of San Francisco on November 7–8, 2003. The conference was the inaugural event of the Bank's new Center for the Study of Innovation and Productivity.

The study of productivity growth cuts across many of the fields and approaches in economics—microeconomics, macroeconomics, and international economics; theoretical and empirical analyses—and it is a subject for students of history as well as of current events. The seven papers presented at this conference highlight the breadth of questions and methodologies of recent research on productivity growth.

Three of the conference papers examine productivity growth at the macro economic level. Kahn and Rich propose a method that aims to improve our ability to identify breaks in trend productivity growth of the types that occurred in the 1970s and in the mid-1990s. While such breaks are easy to spot after the fact, they have proven difficult to recognize in real time. In a theoretical paper, Jones asks how production technologies are determined in the first place. He considers how new ideas affect the development of production possibilities in both the short run and the long run. Manuelli and Seshadri consider the link between innovations and the adoption of new production technologies directly. As a case study of technological diffusion, they examine the long time lag between the invention of the farm tractor and its wide adoption on American farms in the first half of the 20th century.

Two of the papers take a more microeconomic approach. In a theoretical paper, Scotchmer discusses when and why countries engage in intellectual property rights treaties and whether such treaties produce the optimal amount of innovative activity. Lach and Schankerman focus on whether university researchers respond to financial incentives when determining the effort they expend generating inventions. On the basis of these results, they discuss how universities might alter the current compensation system to produce more innovative effort.

The final two papers look at how technology and productivity differentially affect countries and individuals. Considering productivity in an international framework, Hsieh and Klenow examine the extent to which differences in the efficiency of producing investment goods can explain low rates of capital investment in poor countries. Autor, Levy, and Murnane use an array of data and statistical analyses to tie down the relationship between increased computer use in the workplace and the demand for skilled labor. They identify tasks for which computers can substitute for workers and tasks for which computers complement worker skills. They use their results to shed light on the changing relative demand for skilled workers in the U.S. over the last 30 years.

Detecting changes in trend productivity growth

Shifts in trend productivity growth are uncommon and difficult to recognize when they are actually occurring. Kahn and Rich propose and estimate a statistical model in which the rate of trend productivity growth unpredictably switches from a "low-growth" to a "high-growth" regime. Their econometric procedure detects a regime shift from high growth to low growth in the early 1970s, followed by a shift back to high growth in the late 1990s, with a difference between the mean annual growth rates in the two regimes of about 1.5 percentage points. They find that the economy tends to stay in one regime or another for about 20 years on average.

A key assumption of their method is that a common trend underlies long-run movements in real wages, consumption, and productivity. They further assume that this common trend undergoes infrequent shifts between the two growth rate regimes. Because we cannot directly observe which regime the economy is in at any point in time, it must be estimated along with other parameters of their model. They find that estimating a common permanent trend across all three variables does a better job of detecting trend shifts in U.S. data than do methods that are based only on productivity data. They also find that their procedure identifies shifts in regime relatively quickly.

New perspective on production functions

Jones studies how the creation of new "ideas" affects the use of technology and productivity in the economy. In his model, research is directed at finding new ways to produce goods, and the resulting stream of innovations shapes the evolving aggregate production technology that relates inputs of capital and labor to output. At any point in time, producers choose from the available set of production technologies based on the relative costs of inputs. Over time, better ideas are created and the production possibilities frontier shifts out.

This model provides innovation-based microeconomic foundations for a long-run production function of the Cobb-Douglas form that has been widely used in the economics literature and has empirically supported long-run properties. Importantly, Jones's model implies a stable steady state with positive growth, even in the presence of falling relative prices of capital goods, a property that many other production functions fail to possess.

But, the standard Cobb-Douglas function also has some shortcomings at explaining short- and medium-run empirical regularities, which the Jones model has the potential to correct. For one, the Cobb-Douglas model implies that the share of income going to labor is constant over time; but, the empirical evidence, especially from European economies, suggests that this may not be the case, and the Jones model does not impose this restriction. Second, the Cobb-Douglas model implies that capital and labor are just as substitutable in the short run as in the long run. In contrast, the evidence suggests that the degree of substitutability of labor and capital is lower in the short run, a feature also consistent with the Jones model.

Technological diffusion

Manuelli and Seshadri look at one important example of innovation, the tractor. They argue that the gradual diffusion of tractor use on U.S. farms from 1900 to 1960 can be explained by technological improvements in tractor design and by the path of real wages during this period. Empirical studies of the diffusion of new technologies have documented that there can be a long time lag between the introduction of a new technology and its wide adoption. Other researchers have argued that there are many impediments to the immediate adoption of new and more productive technologies; in contrast, this paper aims to explain the slow diffusion in the case of tractors without relying on such frictions.

They find that low farm wages through the 1930s reduced the incentive for farmers to switch from horses to tractors during that period. Real farm wages fell by half during the Great Depression, which further slowed the adoption of tractors on American farms. It was not until the 1940s, when wages experienced rapid growth that tractors became widely adopted. In addition, increases in urban wages during this period caused less-skilled farmers to leave the agricultural sector and, as a result, the average skill of the remaining farmers improved over time. This resulted in concentrations of land in favor of larger-sized farms, which also made the adoption of tractors more profitable. Finally, they find that improvement in the quality of tractors over time, especially after the 1940s, played an important role in encouraging the adoption of tractors.

Intellectual property treaties

In 1995 the World Trade Organization passed the Agreement on Trade Related Aspects of Intellectual Property (TRIPS) which set minimum standards for intellectual property rights protections across countries. Scotchmer considers whether the extension of minimum intellectual property rights, like those embodied in TRIPS, produces socially efficient outcomes. Specifically, she asks whether intellectual property agreements improve consumer welfare by enhancing the cross-border exchange of ideas. Scotchmer addresses this question by developing a theoretical model of bilateral intellectual property rights treaties and then investigating the circumstances under which countries enter or do not enter agreements.

She finds that countries may not independently engage in the socially optimal level of intellectual property rights. For example, when countries are not the same size or have different levels of innovativeness, the desire for intellectual property protections may differ, with smaller or less-innovative countries wanting fewer protections. In such cases, harmonization policies, such as TRIPS, can improve social efficiency by increasing protections that fuel innovative activity.

Incentives and inventions in universities

Lach and Schankerman examine whether university researchers respond to financial incentives when determining their innovative effort. Specifically, the authors ask whether academic researchers would create more and/or higher quality inventions if they were allowed to keep a larger share of the revenues generated from licensing the new technologies. The authors set up a simple model of the research effort decision of academic scientists that allows scientists to direct effort toward creating a greater number of inventions or a higher quality of invention.

Taking this model to the data, they find that scientists do respond to financial incentives, but only on the quality component of their effort decision. Scientists who were permitted to keep the largest share of royalties generated the highest quality inventions, all else equal. Financial incentives had no measurable impact on the number of inventions scientists created. Lach and Schankerman also found that the relationship between royalty share and invention quality was strongest at private universities. With this in mind, they support greater financial remuneration for scientists contributing to the innovative process.

Relative prices and relative prosperity

Hsieh and Klenow examine a well-established relationship between countries' per capita incomes and investment rates in physical capital (equipment, buildings, etc.), evaluated at international prices. The standard story suggests that poor countries have lower purchasing power parity (PPP) investment rates than rich countries because poor countries have low savings rates, due to high tax rates, etc. Hsieh and Klenow argue against this explanation. Using a theoretical model and the predictions from it, they examine an array of nonpolicy alternatives to explain differences in investment across countries.

First, the authors show that investment rates in poor countries only appear low when evaluated at international prices; when valued in the country's own currency, poor countries save and invest at the same rate as rich countries. Second, they argue that the low PPP investment rates in poor countries are not due to low savings rates or to high tax rates or tariffs on investment, but rather owe to low efficiency in poor countries in producing investment goods or exports that can be traded for investment goods.

Skill levels and technological change

Autor, Levy, and Murnane examine the impact of workplace computer use on the demand for different types of workers. They detail what computers are used for and how they substitute for or complement various worker skills. Specifically, they distinguish between routine cognitive or manual tasks that can be performed by following a set of rules and nonroutine problem-solving and communication tasks that require situational thinking and decisionmaking; computers replace the former and complement the latter. They use their measure of job content and data on increasing computer use over time to explain the rising demand for college-educated workers between 1960 and 1998.

They find a strong relationship between shifts in job tasks and the adoption of computer technology over the period; specifically, increased computerization reduced labor input for routine tasks and increased labor input for nonroutine tasks. This pattern occurred both within and across industries and occupations. Based on these calculations, they argue that nearly two-thirds of the relative increase in demand for college-educated workers can be explained by rising workplace computer use. Interestingly, they find that about half of the measured impact of rising workplace computer use owes to increasing requirements within occupations over time; for example, the tasks and requirements for a secretarial job in 1998 involved a much higher level of skills than a secretarial job in 1960, contributing to higher demand for skilled workers in the latter period.

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Conference papers

Papers are available in pdf format at http://www.frbsf.org/economics/conferences/0311/index.html

Autor, David, Frank Levy, and Richard Murnane. 2003. "The Skill Content of Recent Technological Change: An Empirical Exploration." Massachusetts Institute of Technology.

Hsieh, Chang-Tai, and Peter Klenow. 2003. "Relative Prices and Relative Prosperity." Stanford University.

Jones, Charles. 2003. "Growth, Capital Shares, and a New Perspective on Production Functions." University of California, Berkeley.

Kahn, James, and Robert Rich. 2003. "Tracking the New Economy: Using Growth Theory to Detect Changes in Trend Productivity." Federal Reserve Bank of New York.

Lach, Saul, and Mark Schankerman. 2003. "Incentives and Invention in Universities." London School of Economics.

Manuelli, Rodolfo, and Ananth Seshadri. 2003. "Frictionless Technology Diffusion: The Case of Tractors." University of Wisconsin, Madison.

Scotchmer, Suzanne. 2003. "The Political Economy of Intellectual Property Treaties." University of California, Berkeley.

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