Is the Information Technology Revolution Over?*

David M. Byrne, Federal Reserve Board
Stephen D. Oliner, American Enterprise Institute and UCLA
Daniel E. Sichel, Wellesley College

January 2013

Incomplete. Notes, tables, charts, and references are included.

*The views expressed here are ours alone and should not be attributed to the Board of Governors of the Federal Reserve System, its staff, or any of the other institutions with which we are affiliated.

I. Introduction

(See Oliner and Sichel (2002), pp. 15-17, and Oliner, Sichel, and Stiroh (2007), pp. 81-85, for more extensive references to the literature.)

- A number of recent papers have highlighted the slowdown in productivity growth in the United States in the mid-2000s, including Fernald (2012), Gordon (2012), and Jorgenson (2012). As shown in figure 1, labor productivity clearly decelerated around 2004, after having grown rapidly over the previous decade. Gordon, in particular, has argued that the IT revolution (the third industrial revolution) has largely run its course and that the boost to labor productivity growth from those developments wound down in the mid-2000s.

- This paper uses the methodology developed by Oliner and Sichel (2002) and Oliner, Sichel, and Stiroh (2007) to examine this question. This growth accounting methodology is well suited to the task because it focuses on the contribution of IT to labor productivity growth (from both the use and production of IT) and because it can be updated with the most recent data to provide estimates through 2012.
    - We find that the contribution of IT to labor productivity growth over 2004-2012 stepped down to roughly its contribution from the mid-1970s to 1995. This evidence supports the view that IT is no longer providing the boost to growth of labor productivity that it did during the years of the productivity resurgence from 1995 to 2004.
    - Nonetheless, the contribution of IT to labor productivity remains substantial, especially given the small share of the sector in the economy. Much uncertainty attends the future of the IT revolution and whether the growth contribution will remain in the neighborhood of the pre-1995 level or will rise again.

- To think about the future of labor productivity growth in a structured way, we assess the range of plausible growth rates in a steady-state model. This part of the paper allows us to translate alternative assumptions about the pace of technological progress in key sectors of the economy into an overall growth rate of labor productivity.

- Because of the critical role played by technological progress in the semiconductor sector, we also delve more deeply into developments in that industry. The official price indexes for semiconductors published by the BLS show that semiconductor prices are not falling nearly as rapidly as they did prior to the mid-2000s. These price developments are taken by some as evidence that the pace of technical progress in the semiconductor industry has slowed. Such a slowdown would comport well with the narrative developed by Bob Gordon that the IT revolution largely is over.

- On a more hopeful note, we provide evidence that technical progress in the semiconductor industry continues to proceed at a very rapid pace. We show that part of the slower pace of price declines reflects an increase in margins at Intel. We also discuss preliminary results from a separate paper that raise the possibility that BLS has significantly understated the price declines for semiconductors in recent years.

- The continued rapid advance in semiconductor technology offers support for the view that the IT revolution still has room to run.

II. Growth Accounting: Analytical Framework, Data, and Results

A. Analytical Framework

(See Oliner and Sichel (2002), pp. 16-19 and 32-36, and Oliner, Sichel, and Stiroh (2007), pp. 86-89, for more on the analytical framework.)

- Our methodology closely tracks that described in the citations above.

- We decompose labor productivity growth into the contributions from capital deepening, labor composition, and multifactor productivity growth. In estimating the contribution from capital deepening, we focus on three categories of IT: computer hardware, software, and communication equipment. This detail allows us to estimate contributions to labor productivity growth from the ***use*** of IT.

- Following Oliner, Sichel, and Stiroh (2007), we adjust MFP growth for changes in factor utilization and for adjustment costs associated with the installation of new capital.

- We then decompose MFP growth into the contributions from five sectors: computer hardware, software, communications equipment, semiconductors, and all other output. This decomposition allows us to estimate contributions to labor productivity growth from the ***production*** of IT.

B. Data

(See Oliner and Sichel (2002), pp. 20 and 37-42, and Oliner, Sichel, and Stiroh (2007), pp. 89-93, for more on the data.)

- The data we use are largely updates from the series used in our earlier work. However, there are two changes of note with respect to the data on capital:
    - For the period 1987-2010, we are relying on BLS estimates of the contributions of capital deepening for overall capital and for IT capital. Previously, we rolled our own. But BLS is now providing sufficient detail on their website that it makes sense to rely on their numbers.
    - For the periods in which we do roll our own contributions (2011-2012 for both IT and overall capital deepening and the mid-1970s to 1986 for IT capital deepening), we are now working from a higher level of aggregation than we did in earlier papers. Previously, we built up contributions from about 60 different types of capital. We are now building up contributions from fewer types of capital, making use of the data that BLS provides publicly on its website. (We concluded that we weren't buying much from the extra detail and that it would be preferable to track publicly available information as closely as possible.)

C. Results

- Table 1 summarizes our growth accounting results. Lines 2 through 11 show the decomposition of labor productivity growth (which includes the contributions from IT use), while lines 12 through 18 show the decomposition of MFP growth (which identifies the contributions from IT production).

- As shown, labor productivity growth in 2004-2012 dropped back to near its pace prior to 1995, as did growth in MFP. The rapid growth in both measures during 1995-2004 stands in sharp contrast to the slower gains both before and after.

- During 2004-2012, the IT contributions to labor productivity growth are quite similar to those in the period from the mid-1970s to 1995 and are well below the elevated contributions from 1995 to 2004.
    - This is true for both the use of IT (via capital deepening) and the production of IT.
    - As shown in the memo line of the table, the total IT contribution was 0.63 percentage point over 2004-2012, compared with 0.78 percentage point before 1995.

- These results indicate that the extremely large IT contributions to productivity growth that began in the mid-1990s lasted only about a decade. Figure 2 presents the IT growth contributions on an annual basis. As shown, the contributions from IT between 2005 and 2009 were comparable to those in most years before 1995, while the contributions for 2010, 2011, and 2012 were especially low. Part of the reduced contribution during 2010-2012 reflects the ongoing decline in domestic production of computers, communication equipment, and semiconductors (see figure 3). In addition, the contribution from the use of IT was relatively low during these years, possibly because the tepid recovery and the uncertainty surrounding the economic, fiscal, and regulatory outlook led firms to defer discretionary IT investments.

- Despite the downshift in the IT contribution after 2004, the contribution of IT to labor productivity growth remains sizable, accounting for more than 1/3 of the growth in labor productivity over 2004-2012.

- Sorting out the implications of these results for the future of the IT revolution is difficult.
    - One possibility is that the IT revolution is over, as Bob Gordon suggests.
    - Another possibility is that the boost to labor productivity growth is taking a pause during the transition from the PC era to the handheld-device era. Just as a long lag transpired from the development of the PC to the subsequent pickup in labor productivity growth, a lag may also be evident from the development and diffusion of handheld devices to a subsequent acceleration in labor productivity.
    - Perhaps in a number of years, we'll be saying: "In the early 2010s, you could see handheld devices everywhere but in the productivity statistics."

- The outlook for labor productivity growth is taken up in the next section.

III. Outlook for Productivity Growth

A. Steady-state Analysis

(See Oliner and Sichel (2002), pp. 24-30 and 36-37, and Oliner, Sichel, and Stiroh (2007), pp. 130-132, for more on the steady-state analysis.)

- We use the steady-state machinery from Oliner and Sichel (2002).
  - As noted above, the growth accounting model includes four IT sectors and the rest of nonfarm business.
  - We impose a number of steady-state conditions on the model, such as that investment and the capital stock grow at the same rate for each type of capital.
  - In the steady state, the growth of output per hour equals the sum of growth in MFP, the change in labor composition, and the contribution from the capital deepening induced by MFP growth.
  - We specify values for the roughly 30 parameters in the model and then solve for the implied growth in output per hour. In choosing the parameter values, we try to provide bounds around recent values that take account of the range observed over our full sample period. Quite a bit of judgment is involved.

- The results of this steady-state analysis are more pessimistic than those from a similar analysis in Oliner, Sichel, and Stiroh (2007).
  - The selected parameter values imply a range for steady-state growth in labor productivity from about 1.2 percent to about 2.5 percent (see table 2).
  - The midpoint of the range is 1.85 percent, down from 2.3 percent in the analysis five years ago.
  - There are three main sources of the downward revision:
    - A smaller contribution from improvements in the composition of the labor force, which results from the assumption that educational attainment is hitting a plateau. We rely on Dale Jorgenson's work for the projected labor composition effect.
    - Slower MFP growth in the non-IT sectors of the economy. We marked down the projected range for this key parameter of the model because of the very weak MFP growth since 2004.
    - Smaller output shares for the IT sectors. As noted above, domestic production of computers, communication equipment, and semiconductors — all of which have rapid MFP growth — has dropped sharply since 2000. We assume that the future output shares for these sectors remain in a range centered on their current levels.

B. Other Estimates

- As shown in table 3, other analysts have also marked down their projections for future growth in labor productivity.
  - These projections average 1.9 percent, down from 2.3 percent in 2007. This is very similar to the downward revision to our steady-state estimate.

  - For the most part, the projections cover a ten-year horizon, although one projection (Kahn-Rich) refers to the coming five years and another (Fernald) has no explicit horizon.
  - A few of the projections are stale at this point (the CEA projection, for example, is from February 2012) and so may not fully reflect the downbeat tone of the recent data.
  - From a longer historical perspective, the average projected growth of labor productivity, at 1.9 percent, is a shade below the average rate since 1889 (see table 4).

- We would stress that there is a wide confidence band around these projections.
  - Our own steady-state projection spans the range from 1.2 percent (which would be far below the historical average rate) to 2.5 percent (which would be well above the historical average).
  - The only projection in the table with a rigorous statistical confidence range is the estimate from the Kahn-Rich regime-switching model. Their 75 percent confidence band for productivity growth five years ahead runs from slightly below zero to about 4 percent!
  - Suffice it to say, productivity growth is notoriously hard to predict. Almost all analysts have failed to anticipate the major shifts in growth over the past several decades.

IV. Trends in Semiconductor Technology

A. Technology Cycles

(See Aizcorbe, Oliner, and Sichel (2008), pp. 34-36, for more on technology cycles.)

- There is widespread agreement among industry experts that the technology cycles in the semiconductor industry sped up in the mid-1990s.
  - The standard definition of a semiconductor technology cycle is the amount of time required to achieve a 30 percent reduction in the width of the smallest feature on a chip. Since chips are rectangular, a 30 percent reduction in both the horizontal and vertical directions implies about a 50 percent reduction (0.7*0.7) in the area required for the smallest chip component.
  - From roughly 1970 to the mid-1990s, the time needed to achieve this reduction in scaling was about three years. In the mid-1990s, the three-year cycle gave way to a two-year cycle. Jorgenson (2001) was the among the first to bring this change to the attention of the economics profession.
  - Table 5 lists the year of introduction for each successive advance in the scaling (i.e., lithography) frontier for the semiconductor industry as a whole and for the microprocessor (MPU) chips produced by Intel. As shown, Intel is always at or close to the frontier.

- Given these introduction dates, the two-year cycle has remained in effect at Intel through this year (see table 6). Data for the lithography frontier for the semiconductor industry as a whole tell a similar story.

- From an economic perspective, the costs incurred to remain on the two-year cycle are as important as the length of the cycle itself. If it were becoming increasingly costly to stay on the two-year cycle, that would lessen the economic benefits of the advance. Fortunately, that does not appear to be the case.
  - Data released by Intel (in the materials for its 2012 Investor Meeting) show that it has continued to reduce production cost per transistor for frontier MPU chips at a constant rate since the mid-1990s.
  - Although these data are not definitive (they likely exclude R&D costs — we're checking on this), they do paint a favorable picture for cost trends.

- The upshot is that improvements in semiconductor technology and declining costs remain a strong driver for productivity growth.

B. Prices for MPUs

(This section is more detailed than other parts of the notes because there is no other source for much of this information. The material here largely reflects a preview of preliminary work for another paper that will develop new price indexes for MPUs.)

- Despite the continuation of the two-year technology cycle and the persistent downtrend in production costs, the rate of decline in MPU prices — as recorded by BLS in the producer price index (PPI) — has slowed substantially (see figure 4).
  - From 1997 (when the BLS introduced its current methodology) to 2006, MPU prices in the PPI fell at an average annual rate of 50 percent.
  - But the rate of price decline slowed from 37 percent in 2007 to 6 percent in 2011.
  - A similar index constructed by Federal Reserve staff that goes back to 1992 shows that the recent declines in the PPI are the slowest in this 20-year period.

- Part of the slowdown in the rate of price decline since 2006 reflects an increase in Intel's profit margin.
  - As shown in figure 5, Intel's markup of price over average cost increased between 2006 and 2011 to the top end of the range observed over the past two decades. (See Aizcorbe, Oliner, and Sichel (2008), pp. 30, 31, and 38, for a description of how we calculated Intel's markup.)
  - But the rising markup can account for only about 5 percentage points per year of the reduced rate of price decline. So it is a minor player in the explanation of why the price declines in the PPI have slowed so much.

- We think the slower price declines may owe in large part to measurement error.
  - BLS publications (Holdway, 2001) and recent discussions with BLS analysts indicate that the agency is employing wholesale price lists to mitigate the non-response of a key player in the industry.

- We have collected wholesale price lists for Intel for the 1998-2012 period. A price index constructed with these data following BLS's matched-model methodology accelerates dramatically as well, corroborating the BLS results.
- However, these price lists also confirm a change in Intel's pricing strategy pointed out to us by an industry consultant—Intel is much less likely than in the past to drop prices of existing models when a new, closely related model is introduced to the market.
- It seems unlikely to us that major computer manufacturers are willing to continue to pay the same price for an older vintage MPU when a new, technically superior, one is introduced at that price. We have no way of knowing if Intel's major customers actually pay wholesale list prices. But if transaction prices reflect a discount relative to list price that grows as the product ages, the BLS methodology may miss important price declines.

- We use a hedonic approach to generate an alternative to the BLS matched-model index.
  - We employ the same Intel list prices but use only the price first observed when a new model is introduced. The use of this subsample allows us to abstract from the possibility of increasing discounts relative to list prices as a model ages.
  - We control for quality using benchmark performance scores from the System Performance Evaluation Corporation (SPEC: http://www.spec.org). We construct a composite score for each MPU model by taking a geometric mean of performance on the 29 specific tests. We also control for the general purpose of the MPU model, as indicated by Intel ("performance", "mainstream", "value", etc.).
  - Our hedonic index falls faster between 2006 and 2011 than the BLS price index (46 percent per year on average versus 19 percent). In addition, the price declines in our index slow much less (from 56 percent in 2007 to 41 percent in 2011) than in the PPI.
  - We also ran our hedonic analysis using all Intel list prices, not just the first observed. This yielded a price index with a noticeably slower rate of decline between 2006 and 2011 than our preferred hedonic (27 percent versus 46 percent) and relatively little year-to-year variation.

- Limitations of the preliminary work and future directions.
  - SPEC benchmark scores are widely available for MPUs designed for use in servers and in performance and mainstream desktop PCs or workstations. Only a few observations are available, however, for value-class desktop PCs and for laptop PCs of all kinds. We are collecting data from other sources to provide better coverage for these chips.
  - So far we have employed SPEC scores only for the 2006-2011 period. SPEC scores are available back to 1992. We will be extending the analysis to include those earlier periods. The longer time series will provide a more complete picture of the timing and magnitude of any changes in the rate of price decline.
  - We do not control for other aspects of the computer system. Obviously, one cannot test the performance of an MPU without embedding it in a computer system. There are other parameters of these systems that affect performance—e.g.

amount of memory—and many MPUs have multiple benchmark scores from different systems. For our results, we used the median of benchmark scores reported for each chip. We also ran the hedonics using the minimum score. The results were similar for PC MPUs, but somewhat different for server MPUs. We will be exploring ways to better control for these other system components.

- There is a segment of the MPU market where transaction prices move with wholesale list prices. This segment consists of MPUs sold online in small batches for PC upgrades or for use by small-scale system builders. For these chips, BLS' methodology would not be subject to the bias we have described. We are attempting to determine the size of this market, but we believe it is relatively small.
- We do not yet have a similar analysis for the prices of MPU chips sold by AMD, but we do have data in hand that will allow us to produce such results. Although AMD's share of domestic U.S. production is nil, it accounts for a significant share of global MPU sales. Data limitations prevent us from including smaller MPU producers (e.g., IBM, Motorola).
- In addition, it appears likely that important innovations are occurring in other semiconductors that are used in smartphone and other mobile devices. It will be interesting to examine whether the BLS price indexes for these chips are subject to bias.

V. Conclusions

Returning to the questions posed in the introduction, the answers implied by our analysis are as follows:

- What do the latest data say about the IT contribution to productivity growth?
  - The contribution from the <u>use</u> of IT capital has moved down sharply. Since 2004, it looks similar to that over 1976-95.
  - The contribution from the <u>production</u> of IT capital also has dropped, largely because a lot of production has moved abroad.
  - Even so, IT has continued to make a sizable contribution to growth.

- What is the outlook for trend growth of labor productivity?
  - The midpoint of the range from the steady-state analysis is 1.85 percent, down from 2.3 percent as of 2007.
  - Other analysts have also revised down their estimates. The average of these estimates is 1.9 percent, a shade below the long-run mean.

- Are improvements in semiconductor technology still proceeding at a rapid pace?
  - MPUs are still on a two-year cycle, and costs are continuing to decline rapidly. This is an encouraging sign about the prospects for growth.
  - Despite these favorable trends, BLS data show a shift to much slower price declines for MPUs. A small part of the explanation is that Intel's price-cost markup has moved higher. More important is the possibility that BLS has significantly understated price declines in recent years.

Table 1. Contributions to Growth of Labor Productivity in the Nonfarm Business Sector[a]

	1976-1995 (1)	1995-2004 (2)	2004-2012 (3)	Change at 1995 (2) – (1)	Change at 2004 (3) – (2)
1. Growth of labor productivity[b]	1.40	3.06	1.60	1.66	-1.46
Contributions (percentage points):					
2. Capital deepening	.69	1.22	.79	.53	-.43
3. IT capital	.44	.78	.38	.34	-.40
4. Computer hardware	.20	.38	.13	.18	-.25
5. Software	.18	.27	.18	.09	-.09
6. Communication equipment	.07	.13	.07	.06	-.06
7. Other capital	.25	.44	.40	.19	-.04
8. Labor composition	.30	.22	.34	-.08	.12
9. Multifactor productivity (MFP)	.40	1.62	.47	1.22	-1.15
10. Effect of adjustment costs	.05	.07	-.02	.02	-.09
11. Effect of utilization	.00	-.07	.17	-.07	.24
12. MFP after adjustments	.36	1.62	.32	1.26	-1.30
13. IT-producing sectors	.34	.69	.25	.35	-.44
14. Semiconductors	.09	.37	.11	.28	-.26
15. Computer hardware	.14	.15	.05	.01	-.10
16. Software	.05	.10	.06	.05	-.04
17. Communication equipment	.05	.07	.03	.02	-.04
18. Other nonfarm business	.02	.93	.07	.91	-.86
Memo:					
19. Total IT contribution[c]	.78	1.47	.63	.69	-.84

Source. Authors' calculations.
a. Detail may not sum to totals due to rounding.
b. Measured as 100 times average annual log difference for the indicated years.
c. Sum of lines 3 and 13.

Table 2. Growth of Labor Productivity in the Nonfarm Business Sector: Steady-State Results

	Using Lower Bound Parameters	Using Upper Bound Parameters
Growth of labor productivity (percent per year)	1.19	2.46
Contributions (in percentage points):		
Induced capital deepening	.82	1.47
Change in labor composition	.07	.07
Growth of MFP	.31	.92
Memo:		
MFP growth, other nonfarm business (percent per year)	.07	.47

Source: Authors' calculations.

Table 3. Alternative Projections of Growth of Labor Productivity
(Percent per year)

Source	As of 2007	As of 2012
1. This paper – midpoint of steady-state range	2.3	1.85
2. Congressional Budget Office	2.3	2.2
3. Council of Economic Advisers	2.6	2.3
4. John Fernald	n.a.	1.9
5. Robert Gordon	2.0	1.75
6. Dale Jorgenson and coauthors[a]	2.5	1.5
7. James Kahn and Robert Rich	2.5	1.8
8. Survey of Professional Forecasters[b]	2.2	1.85
Average of lines 2 through 8	***2.3***	***1.9***

Sources. 2007 estimates from Oliner, Sichel, and Stiroh (2007), table 12. 2012 estimates from Congressional Budget Office (2012), table 2-3; Council of Economic Advisers (2012), table 2-3; Fernald (2012), "Benchmark Scenario" in table 2; Gordon (2010), with adjustment provided in private correspondence; Jorgenson and Vu (2013), "Base Case" on slide 9; Kahn-Rich Productivity Model Update (November 2012), posted at http://www.newyorkfed.org/research/national_economy/richkahn_prodmod.pdf; Federal Reserve Bank of Philadelphia, *Survey of Professional Forecasters*, February 10, 2012, table 7.
a. Projection applies to the period 2010-20. In private correspondence, Dale Jorgenson indicated that the projection for 2012-2022 would be similar.
b. Median forecast in the survey.

Table 4. Growth of Labor Productivity: Historical Averages[a]
(Percent per year)

Long History			Subperiods since 1947			
1889-2012	1889-1947	1947-2012	1947-1974	1974-1995	1995-2004	2004-2012
2.1	2.0	2.2	2.6	1.5	3.0	1.6

Source. Authors' calculations using data from data from Kendrick (1961) for 1889-1947 and BLS for 1947-2012.
a. Measured as 100 times the average log difference over indicated period, based on annual average data. Data for 1889-1947 pertain to the private nonfarm economy, whereas data for 1947-2012 pertain to the nonfarm business sector.

Table 5. Year of Introduction for New Semiconductor Technology

Process (nanometers)	Lithography Frontier	Intel MPU Chips
10,000	1969	1971
8000	1972	n.a.
6000	n.a.	1974
5000	1974	n.a.
4000	1976	n.a.
3000	1979	1979[a]
2000	1982	n.a.
1500	1984	1982
1250	1986	n.a.
1000	1988	1989
800	1990	1991
600	1993	1994
350	1995	1995
250	1997	1997
180	1999	1999
130	2001	2001
90	2003	2004
65	2005	2005
45	2007	2007
32	2010	2010
22	2012	2012

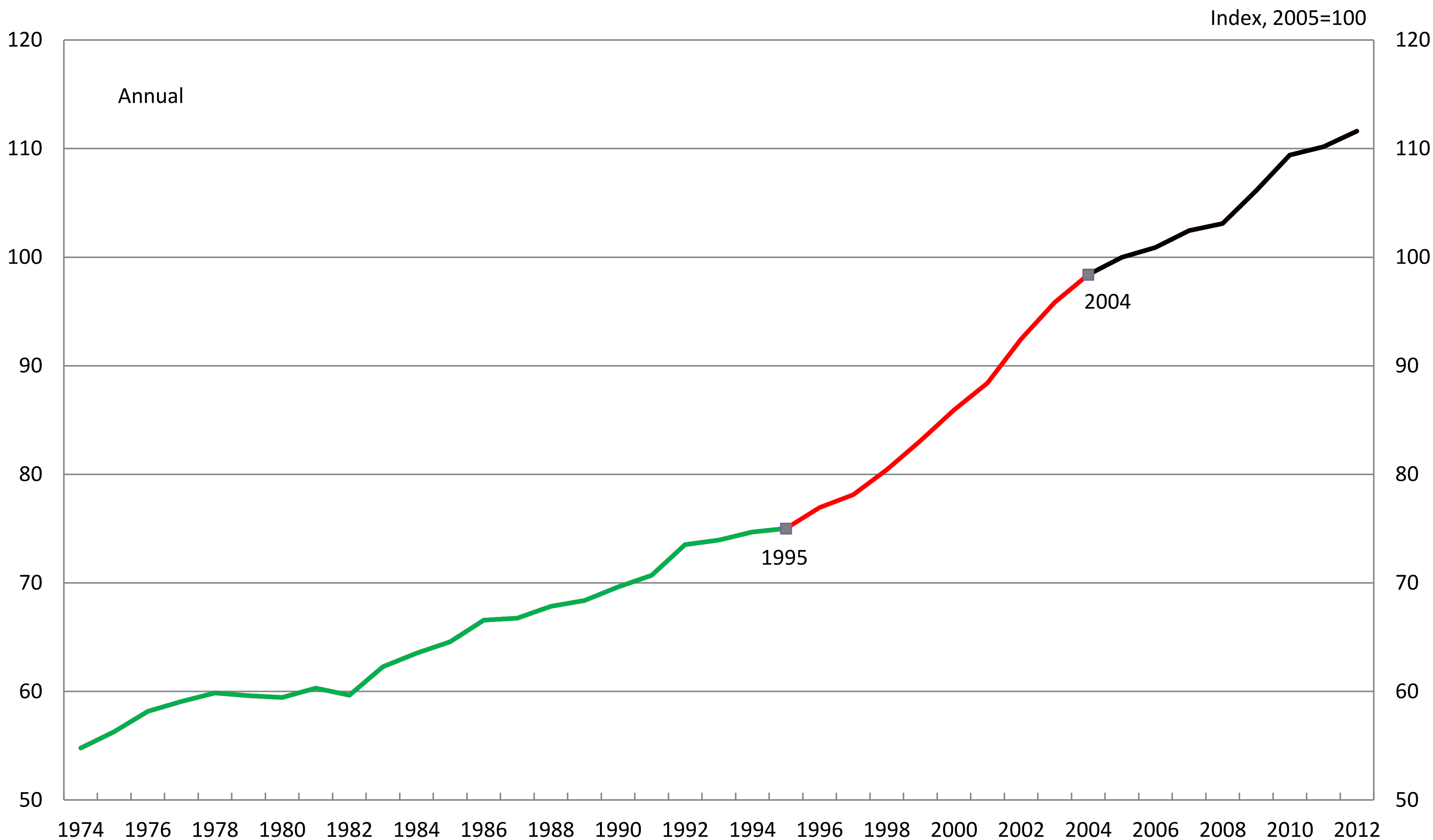
Source. Lithography frontier: VLSI Research Inc. (2006) for the 65 nanometer and earlier processes and private correspondence with Dan Hutcheson (November 10, 2012) for the more recent processes. Intel MPU chips: http://www.intel.com/pressroom/kits/quickreffam.htm.
a. Intel began making MPU chips with this process in 1979. We omitted Intel's earlier use of the 3000 nanometer process (starting in 1976) to produce less complex devices, such as scales.
n.a.: Not available.

Table 6. Semiconductor Technology Cycles
(Years needed for 30 percent reduction in scaling)

Lithography Process			Intel MPU Chips	
Period	Years		Period	Years
1969-1993	3.0		1971-1994	2.9
1993-2012	2.0		1994-2012	1.9
1993-2003	1.9		1994-2004	1.9
2003-2012	2.3		2004-2012	2.0

Source: Authors' calculations from data in table 5.

Figure 1. Labor Productivity, Nonfarm Business Sector



Source: BLS

Figure 2. Contributions from IT to Growth in Labor Productivity

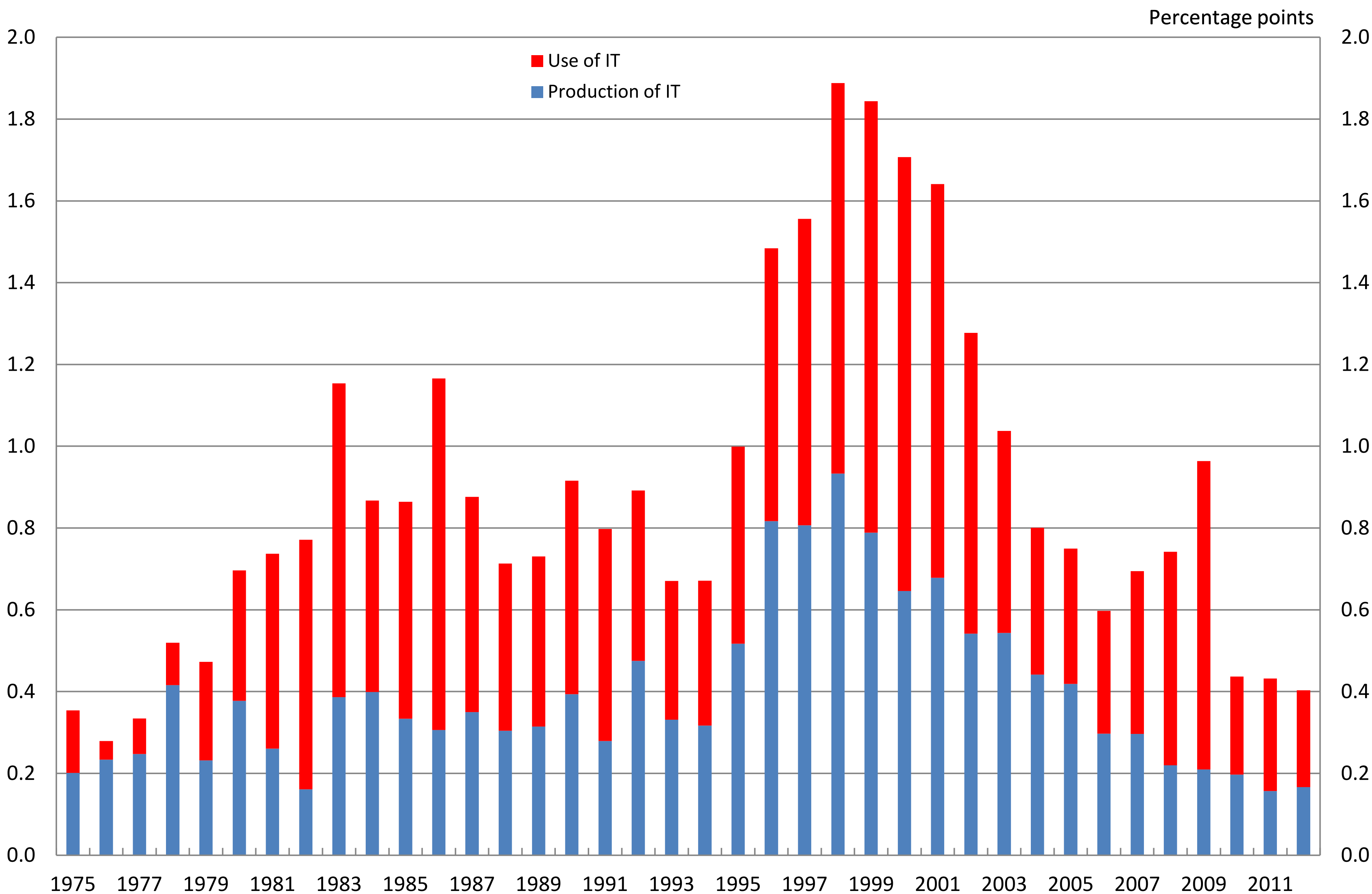


Figure 3. Current-dollar Output Shares for IT Industries

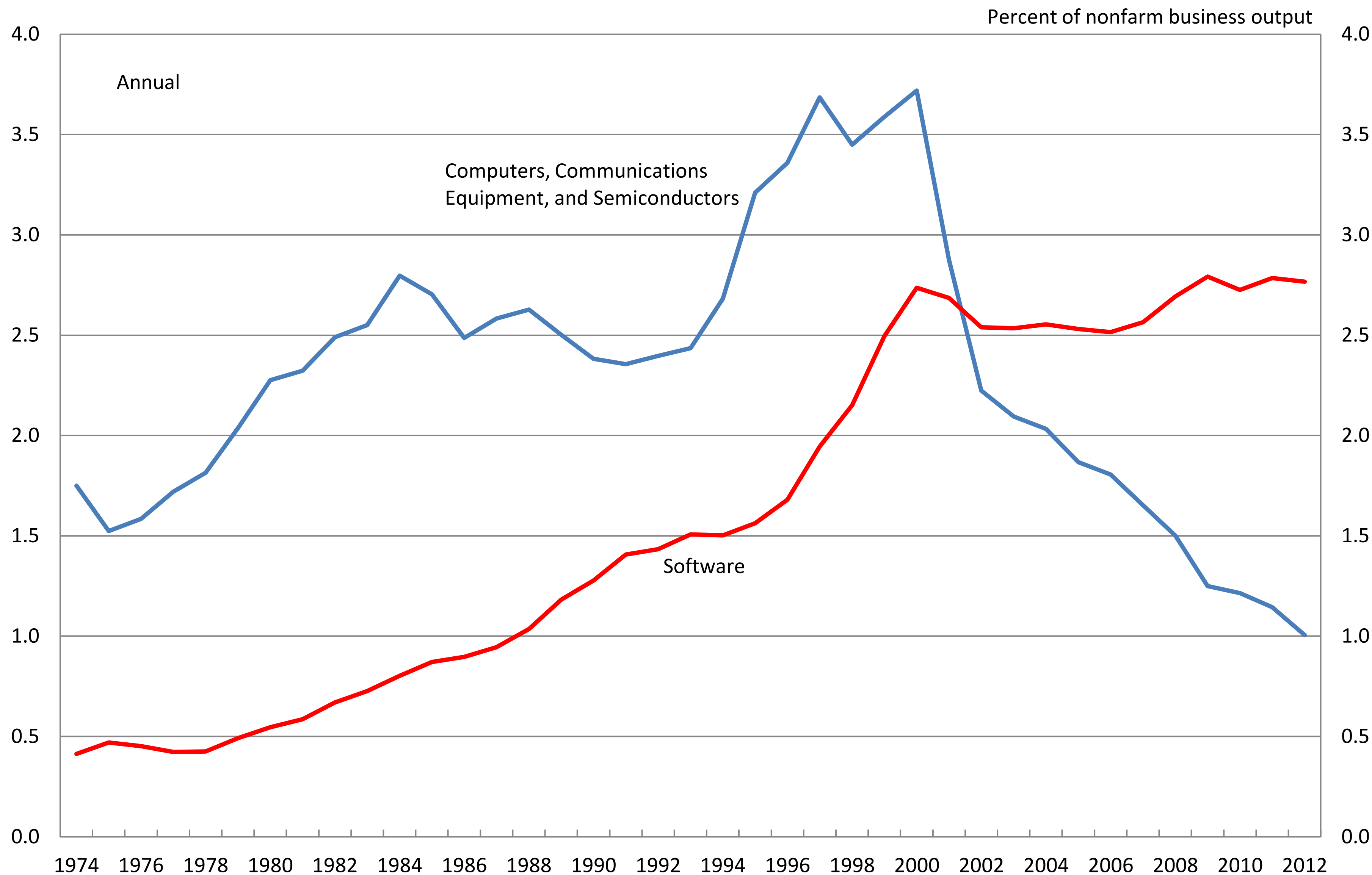
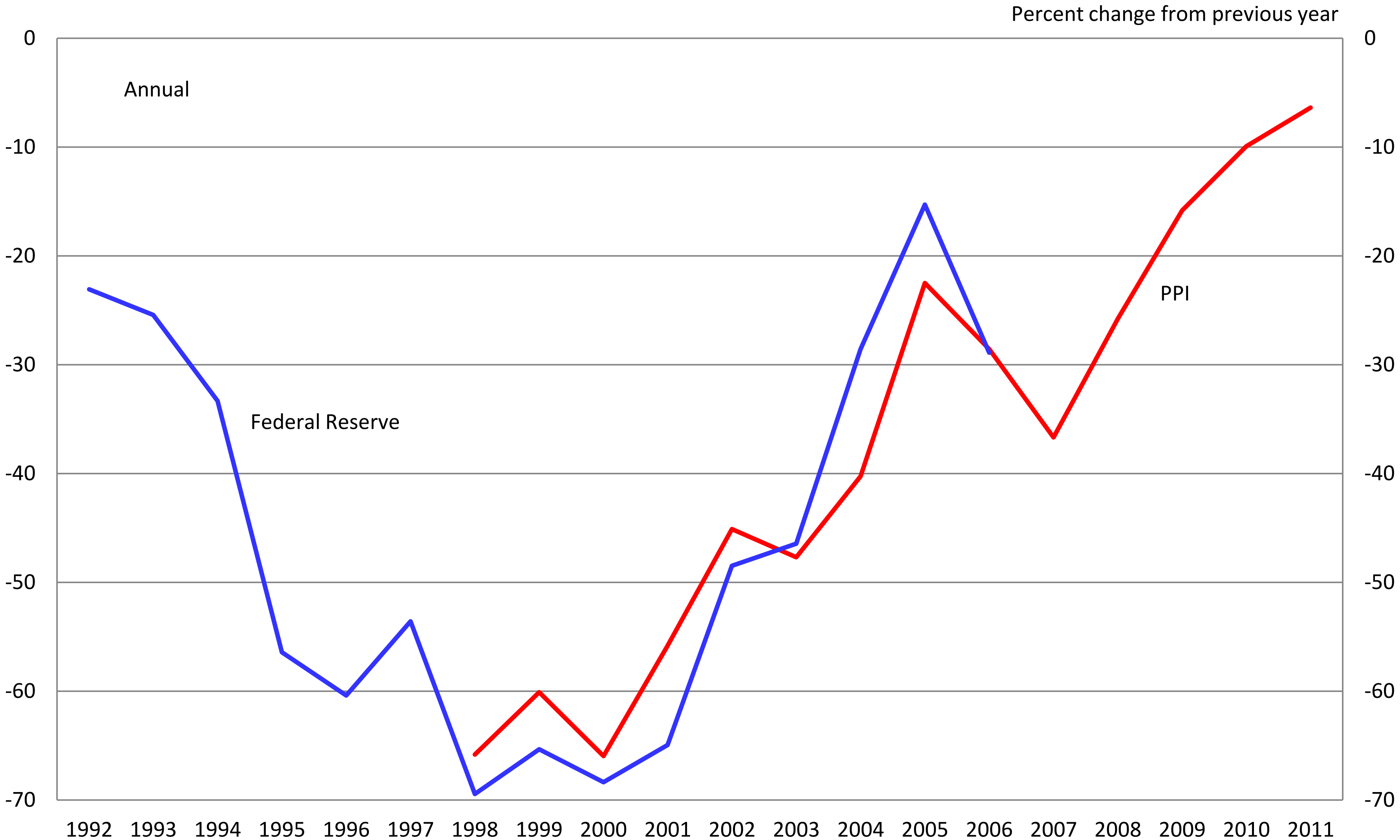
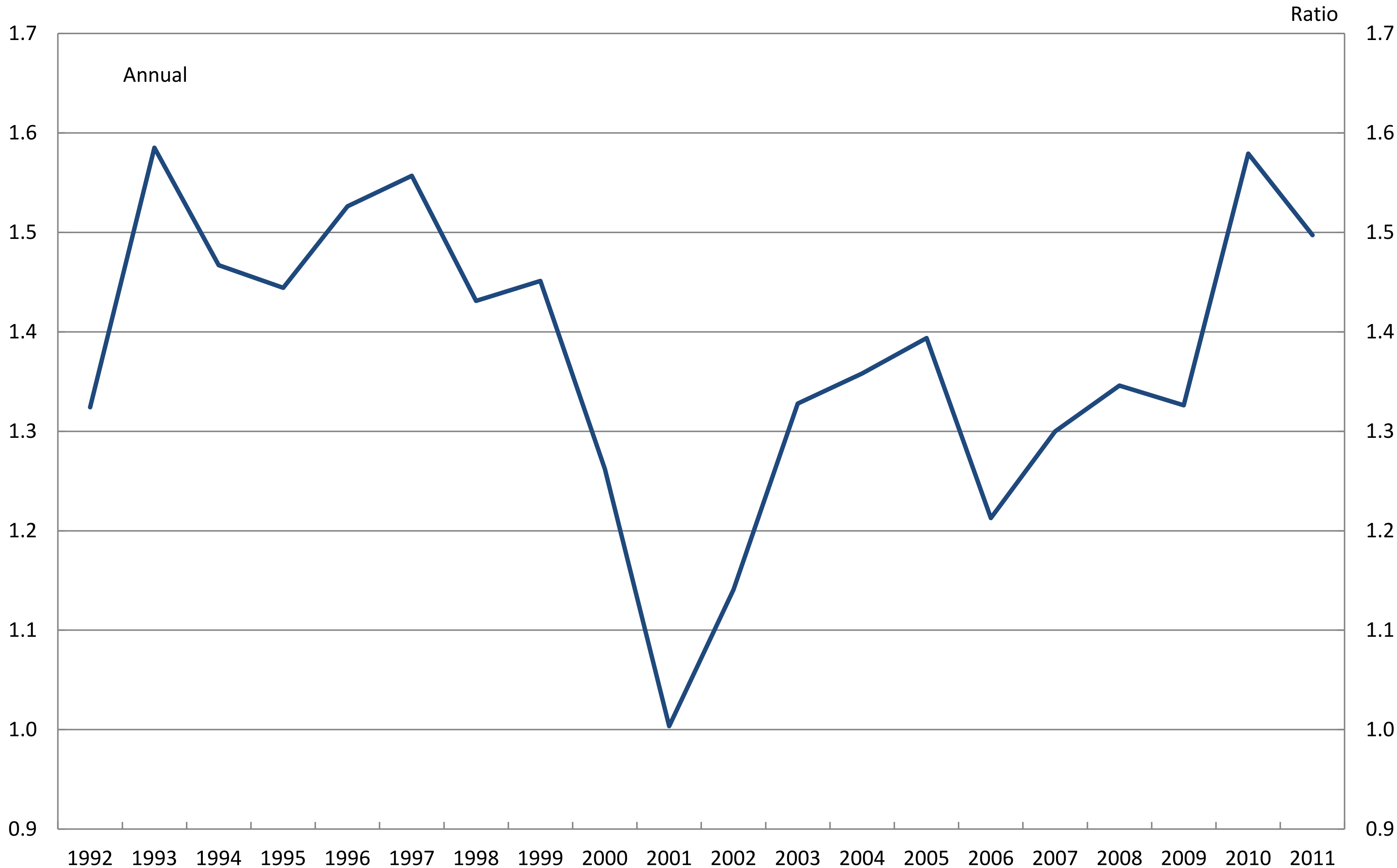


Figure 4. Price Indexes for Microprocessors (MPUs)



Source. BLS and Federal Reserve Board

Figure 5. Intel's Price-Cost Markup



Source. Compustat and company 10-K statements.

References

Aizcorbe, Ana, Stephen D. Oliner, and Daniel E. Sichel. 2008. "Shifting Trends in Semiconductor Prices and the Pace of Technological Progress." *Business Economics* 43(3): 23-39.

Congressional Budget Office. 2012. *An Update to the Budget and Economic Outlook: Fiscal Years 2012 to 2022.* Washington (August). http://www.cbo.gov/sites/default/files/cbofiles/attachments/08-22-2012-Update_to_Outlook.pdf

Corrado, Carol, and Charles Hulten. 2012. "Innovation Accounting." The Conference Board, Economics Program Working Paper #12-04 (October).

Council of Economic Advisers. 2012. *Economic Report of the President*. Washington (February). http://www.whitehouse.gov/sites/default/files/microsites/ERP_2012_Complete.pdf

Fernald, John. 2012. "Productivity and Potential Output before, during, and after the Great Recession." Federal Reserve Bank of San Francisco Working Paper 2012-18. September. http://www.frbsf.org/publications/economics/papers/2012/wp12-18bk.pdf

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

Gordon, Robert J. 2010. "Revisiting U.S. Productivity Growth over the Past Century with a View of the Future." NBER Working Paper 15834. March. http://www.nber.org/papers/w15834.

Gordon, Robert J. 2012. "Is U.S. Economic Growth Over? Faltering Innovation Confronts the Six Headwinds." NBER Working Paper 18315. August. http://www.nber.org/papers/w18315.

Holdway, Michael. 2001. "An Alternative Methodology: Valuing Quality Change for Microprocessors in the PPI." Unpublished paper presented at Issues in Measuring Price Change and Consumption Conference, Bureau of Labor Statistics, Washington DC, June 5-8, 2000. Revised January 2001.

Jorgenson, Dale W. 2001. "Information Technology and the U.S. Economy." *American Economic Review* 91(1): 1-32.

Jorgenson, Dale W. 2012. "A Prototype Industry-Level Production Account for the United States, 1947-2010." Presentation at the WIOD Conference, Groningen, The Netherlands, April 25.

Jorgenson, Dale W., Mun S. Ho, and Kevin J. Stiroh. 2002. "Projecting Productivity Growth: Lessons from the U.S. Growth Resurgence." Federal Reserve Bank of Atlanta *Economic Review* 87 (Third Quarter): 1-13.

Jorgenson, Dale W., and Kevin J. Stiroh. 2000. "Raising the Speed Limit: U.S. Economic Growth in the Information Age." *Brookings Papers on Economic Activity* 2000(1): 125-211.

Jorgenson, Dale. W. and Khuong Vu. 2013. "Economic Growth in the G7 and the G20." Presentation at the ASSA meetings, San Diego, CA. January 5.

Kendrick, John W. 1961. *Productivity Trends in the United States*. National Bureau of Economic Research. Princeton University Press.

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

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

Oliner, Stephen D., Daniel E. Sichel, and Kevin J. Stiroh. 2007. "Explaining a Productive Decade." *Brookings Papers on Economic Activity* 2007(1): 81-152.

VSLI Research Inc. (2006). "Did Acceleration from a Three to Two Year Node Life Really Occur?" *The Chip Insider*, April 6.