Technology and U.S. Wage Inequality: A Brief Look

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The industrial revolution of the eighteenth and nineteenth centuries left in its wake a large body of literature, both popular and scholarly, arguing that technology had wrought fundamental changes to the labor market. Some argued that as important as the steam engine and new machinery were to this new economy, "mental steam power" and "intellectual machinery"—the ability of workers to interact with the new technologies—was of equal or greater significance. Even as debate about that earlier period continues more than one hundred years later, a new debate—with interesting parallels to that earlier discussion—has ensued about the effect of computers and other information and communications technology on the labor market.[1]

Developments in personal computers, for example, led *Time* magazine to make the device its 1982 "Person of the Year" and argue that "the information revolution . . . has arrived . . . bringing with it the promise of dramatic changes in the way people live and work, perhaps even in the way they think. America will never be the same." By the late 1980s and early 1990s, labor market analysts were finding it apparent that wage inequality had risen, and a series of papers argued that these two developments—rapid technological change and rising wage inequality—were related.[2] These papers and the large literature that followed have paved the way for the virtually unanimous agreement among economists that developments in computers and related information technologies in the 1970s, '80s, and '90s have led to increased wage inequality.

In the labor economics literature this consensus view has become known as the "skill-biased technological change" (SBTC) hypothesis. Specifically, this hypothesis is the view that a burst of new technologies led to an increased demand by employers for highly skilled workers (who are more likely to use computers) and that this increased demand led to a rise in the wages of the highly skilled relative to those of the less skilled and therefore an increase in wage inequality.

In this paper, which is a substantially abridged version of Card and DiNardo (2002), we reconsider the evidence for the SBTC hypothesis. We focus considerable attention on changes over time in overall wage inequality and in the evolution of relative wages of different groups of workers. In doing so, we conclude that despite the considerable attention this view has received in the literature, SBTC falls far short of unicausal explanation of the substantial changes in the U.S. wage structure of the 1980s and 1990s. Indeed, although there have been substantial changes in the wage structure in the last thirty years, many of which are documented here, SBTC by itself does not prove to be particularly helpful in organizing or understandings these changes. Based on the evidence, we conclude that it is time to re-evaluate the case that SBTC offers a satisfactory explanation for the rise in U.S. wage inequality in the last quarter of the twentieth century.

An Empirical Framework for Understanding SBTC

There are many theoretical versions of skill-biased technological change. To help fix ideas, this paper focuses on a simple SBTC formulation, versions of which have helped guide the large empirical literature in labor economics.[3] Assume that aggregate labor demand is generated by a constant elasticity of substitution (CES) production function of the form

$$(1)\quad Y = f(N_H, N_L) = A\,[\alpha(g_H N_H)^{(\sigma-1)/\sigma} + (1-\alpha)\,(g_L N_L)^{(\sigma-1)/\sigma}]^{\sigma/(\sigma-1)},$$

where Y represents the value of output; N_H represents the labor input (employment or hours) of high-skilled workers; H_L represents the input of low-skilled labor; $\sigma > 0$ is the elasticity of substitution between the labor inputs; and A, α, g_H, and g_L are technological parameters that can vary over time.[4] In many empirical applications N_H is measured by the number of college graduates (or "college-equivalent" workers), and N_L is measured by the number of high-school graduates (or "high-school-equivalent" workers.) For given values of the technology parameters, the relative demand for high-skilled labor is determined by setting the ratio of the marginal product of the two groups equal to the ratio of their wages, w_H/w_L. Taking logarithms of the resulting expression and first-differencing over time leads to a simple expression that has been widely used to discuss the evolution of relative wages:

$$(2)\quad \Delta\log[w_H/w_L] = \Delta\log[\alpha/(1-\alpha)] + (\sigma-1)/\sigma\Delta\log[g_H/g_L] - 1/\sigma\Delta\log[N_H/N_L].$$

The equation is assumed to hold true for every time period (typically a year). If the relative supply of the two skill groups is taken as exogenous, this equation completely determines the evolution of relative wages over time. The technological parameters cannot be observed directly but are often inferred by making some assumptions about how they evolve over time. From equation 2, two observations follow directly.

First, changes in relative wages must reflect either changes in relative supplies or changes in technology. Other features of the labor market that potentially affect relative wages (such as the presence of unions, institutional wage floors, etc.) are essentially ignored. In the absence of technological change, the relative wage of high-skilled workers varies directly with their relative supply. Despite some problems of identification, there exists a "consensus" estimate of $\sigma \approx 1.5$ when the two skill groups are college and high-school workers.[5] This estimate implies, for example, that a 10 percent increase in the relative proportion of college-educated workers lowers the relative wage of college-educated workers by 6.6 percent. Since the relative proportion of highly educated workers has been rising throughout the past several decades, the only way to explain a rise in the relative wage of skilled workers (and hence a rise in wage inequality) is through changes in the technology parameters α or g.

Second, skill-biased changes in technology lead to changes in wage inequality. A shift in the parameter A, or an equiproportional shift in g_H and g_L, leaves the relative productivity of the two skill groups unchanged and affects only the general level of wages. SBTC involves either an increase in α or an increase in g_H relative to g_L. A rise in α raises the marginal productivity of skilled workers and at the same time lowers the marginal productivity of unskilled workers. This type of technological change has been referred to as "extensive" SBTC; Johnson (1997) gives as an example of extensive SBTC the introduction of robotics in manufacturing. The other situation, sometimes referred to as "intensive" SBTC, arises when technological change enhances the marginal productivity of skilled workers without necessarily lowering the marginal product of unskilled workers.[6]

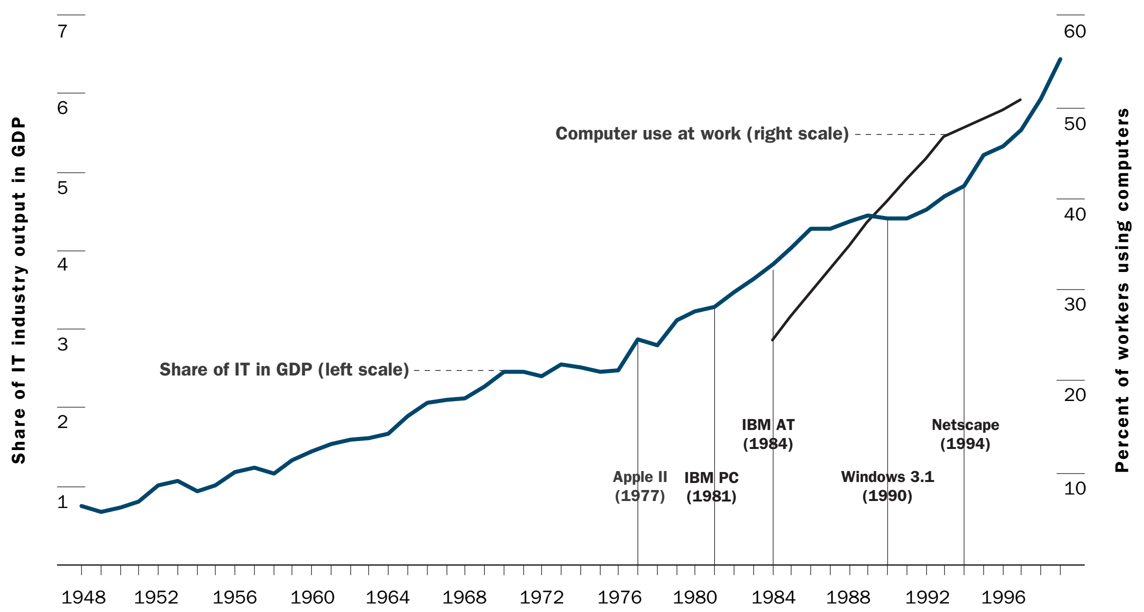
Technology or Tautology?

As has been observed, in this framework SBTC can be defined to exist whenever changes in relative wages are not inversely related to changes in relative supply. Indeed, the test for SBTC proposed by Katz and Murphy (1992) is a multifactor version of this point. Given a priori qualitative or quantitative evidence on how different skill groups are affected by changes in technology, however, the SBTC hypothesis can be tested using data on relative wages and relative labor supplies of different education/age groups, and we proceed to do so in a number of ways.

Aggregate trends in technology. A first task in making the SBTC hypothesis testable is to quantify the pace of technological change. The most widely cited source of SBTC in the 1980s and 1990s is the personal computer (PC) and related technologies, including the Internet. Chart 1 presents a timeline of key events associated with the development of personal computers, plotted with two simple measures of the extent of computer-related technological change. Although electronic computing devices were

CHART 1

Measures of Technological Change



Source: Jorgenson (2001) and authors' analysis of October Current Population Survey, various years

developed during World War II, and the Apple II was released in 1977, many observers date the beginning of the computer revolution to the introduction of the IBM-PC in 1981. This development was followed by the IBM-XT (the first PC with built-in disk storage) in 1982 and the IBM-AT in 1984. As late as 1989, most personal computers used Microsoft's disk operating system (DOS). More advanced graphical-interface operating systems gained widespread use only with the introduction of Windows 3.1 in 1990.

Some analysts have drawn a sharp distinction between stand-alone computing tasks (such as word-processing or database analysis) and organization-related tasks (such as inventory control, supply-chain integration, and internet commerce) and argue that innovations in the latter domain are the major source of SBTC.[7] This reasoning suggests that the evolution of network technologies is at least as important as the development of personal computer technology. The first network of mainframe computers (the ARPANET) began in 1970 and had expanded to about 1,000 host machines by 1984.[8] In the mid-1980s the National Science Foundation laid the backbone for the modern Internet by establishing NSFNET. Commercial restrictions on the use of the Internet were lifted in 1991, and the first U.S. site on the World-Wide Web was launched in December 1991.[9] Use of the Internet grew very rapidly after

1. See Berg and Hudson (1992) and Crafts and Harley (1992) for two very different views of the industrial revolution.
2. See, for example, Bound and Johnson (1992); Juhn, Murphy, and Pierce (1993); Levy and Murnane (1992); and Katz and Murphy (1992).
3. See, for example, Bound and Johnson (1992); Berman, Bound, and Griliches (1994); and Autor, Katz, and Krueger (1998). For a more complete discussion, see the longer version in Card and DiNardo (2002).
4. This model can be easily extended to include capital or other inputs provided that labor inputs are separable and enter the aggregate production function through a subproduction function like equation 1.
5. See Katz and Murphy (1992) and Autor and Katz (1999).
6. Note that it is necessary to assume $\sigma > 1$ in order for a rise in g_H relative to g_L to increase the relative wage of skilled workers. The distinction between the four parameters (A, α, g_H, g_L) is somewhat artificial because one can always rewrite the production function as $Y = [c_H N_H^{(\sigma-1)/\sigma} + c_L N_L^{(\sigma-1)/\sigma}]^{\sigma/(\sigma-1)}$ by suitable definition of the constants c_H and c_L. The relevant question is how the pair (c_H, c_L) evolves over time.
7. This distinction is emphasized by Bresnahan (1999) and Bresnahan, Brynjolfsson, and Hitt (2002).
8. See Hobbes' Internet Timeline at www.zakon.org/robert/internet/timeline.
9. The World-Wide Web was invented at CERN (the European Laboratory for Particle Physics) in 1989–90.

the introduction of Netscape's Navigator program in 1994: The number of Internet hosts rose from about one million in 1992, to twenty million in 1997, and to one hundred million in 2000.

Qualitative information on the pace of technological change is potentially helpful in drawing connections between specific innovations and changes in wage inequality. For example, the sharp rise in wage inequality between 1980 and 1985 (discussed below) points to technological innovations that occurred very early in the computer revolution (around the time of the original IBM-PC) as the key skill-biased events. By comparison, innovations associated with the growth of the Internet presumably had very limited impact until the mid-1990s. Nevertheless, comparisons of relative timing are subject to substantial leeway in interpretation, depending on lags in the adoption of new technologies.

While some of the early rise in inequality may have been due to rapid technological change, we suspect that the increase in the early 1980s is largely explained by other plausible—albeit relatively mundane—factors.

An alternative approach is to attempt to quantify recent technological changes by measuring the relative size of the information technology (IT) sector in the overall economy. One such measure, taken from Jorgenson (2001), is plotted in Chart 1. Notwithstanding the obvious difficulties with the interpretation of such a simplified measure by a fairly broad measure—IT output as a percentage of total gross domestic product—information technology has grown steadily in importance since 1948, with sustained growth over the past two decades and a pronounced upsurge in the late 1990s.[10] The rapid expansion of the IT sector in the late 1990s has attracted much attention, in part because aggregate productivity growth rates also surged between 1995 and 2000. Many analysts (including Basu, Fernald, and Shapiro 2001) have argued that this was the result of an intensive burst of technological change in the mid- to late 1990s.

A third approach, pioneered by Krueger (1993), is to measure the pace of computer-related technological change by the fraction of workers who use a computer on the job. The thin black line in Chart 1 plots the overall fraction of workers who reported using a computer in 1984, 1989, 1993, and 1997.[11] Rates of on-the-job computer use, like the IT output share, show substantial growth over the past two decades—from 25 percent in 1984, to 37 percent in 1989, and to 50 percent in 1997. Nevertheless, the fact that one-quarter of workers were using computers on the job in 1984 suggests that some of the impact of computerization on the workforce preceded the diffusion of personal computers. Indeed, Bresnahan (1999) has estimated that as early as 1971 one-third of U.S. workers were employed in establishments with mainframe computer access. Specialized word-processing machines that predated the personal computer were also widely in use in the early 1980s. The absence of systematic data prior to 1984 makes it hard to know whether computer use expanded more quickly in the early 1980s than in the late 1970s or the late 1980s, which in turn makes it difficult to compare changes in the rate of computer use with changes in wage inequality, especially in the critical early years of the 1980s.[12]

While none of the available indicators of technological change is ideal, all of the indicators suggest that IT-related technological change has been going on since at least the 1970s and has continued throughout the 1980s and 1990s. Moreover, some evidence (based on the size of the IT sector, the pace of innovations associated with the Internet, and aggregate productivity growth) suggests that the rate of technological change accelerated in the 1990s relative to the 1980s.

Whose productivity was raised by recent changes in technology? The second task in developing an empirically testable version of the SBTC hypothesis is to specify which skill groups have their relative productivity raised by SBTC. There are two main approaches to this issue. The first, articulated by Autor, Katz, and Krueger (1998), is to assume that groups that are more likely to use computers have skills that are more complementary with computers and experience bigger gains in productivity with continuing innovations in computer technology.[13] We refer to this as the "computer-use/skill-complementarity" view of SBTC. An alternative, advanced by Juhn, Murphy, and Pierce (1991, 1993), is to assume that recent technological changes have raised the relative productivity of more highly skilled workers along every dimension of skill, leading to an expansion of the wage differentials between groups.[14] We refer to this as the "rising-skill-price" hypothesis. As it turns out, the two approaches yield similar implications for comparisons across some dimensions of the wage structure but different implications for others. Throughout, we will refer to either version or both versions of SBTC as appropriate.

To set the stage, the table on page 50 shows patterns of relative computer use on the job by different skill groups in 1984, 1989, 1993, and 1997. Rates of computer use tend to be higher for those with more schooling. High-school graduates are three to four times more likely to use computers on the job than dropouts, and college graduates are about twice as likely to use computers as those with only a high-school diploma. Interestingly, although overall computer use rates have risen, the relative usage rates of different education groups have remained fairly stable. Since the wage differentials between education groups are bigger today than at the start of the 1970s, this fact would appear to be consistent with the computer-use/skill-complementarity view. Moreover, since better-educated workers earn higher wages, an increase in the wage differential between the highly and less highly educated is also consistent with the rising-skill-price view of SBTC.

The data in the table also show that women are more likely to use computers at work than men, and blacks are less likely to use computers than whites. Although the gender and race gaps closed slightly in the early 1990s, the male-female and black-white gaps remain relatively large. To the extent that complementarity with computer-based technologies is measured by computer use rates, these patterns suggest that recent technological changes should have led to upward pressure on women's wages relative to men's and downward pressure on black workers' wages relative to whites'. In the case of the race differential, the relative wage approach to gauging the impact of SBTC leads to a similar conclusion.[15] In the case of the gender differential, however, the two methods are inconsistent. Women earn less than men and, as with the racial wage gap, part of the gender gap is usually attributed to differences in unobserved skills. Thus, the argument that recent technological changes have raised the relative productivity of more highly paid workers—the rising-skill-price view of SBTC—suggests that computer technology should have led to a widening of the male-female wage gap.

Simple tabulations of computer use rates by education and gender hide an important interaction between these two factors, however. The education gradient in computer use is much bigger for men than women while differences in computer use by gender are much smaller for better-educated workers. Indeed, as shown in the table, college-educated men are more likely to use a computer than college-educated women. To the extent that computer use indexes the relative degree of complementarity with new technology, as assumed by the computer-use/skill-complementarity version of SBTC, computer technology should have widened gender differentials for the most highly educated and narrowed them for the least educated. By contrast, since men earn more than women at all educational levels, the rising-skill-price view of SBTC suggests that the gender gap should have expanded at all educational levels. Although the data are not reported in the table, we have also examined the interactions between gender and race. Compared to the interaction between education and gender, however, the race-gender interactions are relatively modest.

Finally, an examination of computer use rates by age suggests that computer use has expanded slightly faster for older workers than for younger workers. As shown in more detail in Card and DiNardo (2002), computer use rates in the early 1980s were declining slightly with age. By the late 1990s, however, the age profile of computer use was rising slightly between the ages of twenty and forty-five and declining after age fifty. These observations suggest another divergence between the two versions of SBTC. Based on the age profiles of computer use, SBTC may have led to a reduction in older workers'

10. See Oliner and Sichel (2000) and Gordon (2000) for interesting discussions of some of these issues.

11. These data are based on responses to questions in the October Current Population Surveys for workers estimated to be out of school. See Card and DiNardo (2002) for details.

12. Card and DiNardo (2002), using data from the Information Technology Industry (ITI) Council on annual shipments of different types of computers since 1975, find that series constructed from this data show fairly steady growth in shipments from 1975 to 1984.

13. Note that this hypothesis does not necessarily imply that individuals who use computers will be paid more or less than people in the same skill group who do not.

14. To be slightly more formal, assume that the log of the real wage of individual i in period t (w_{it}) is a linear function of a single index of individual ability $a_i = x_i\beta + u_i$, where x_i is a set of observed characteristics and u_i represents unobserved characteristics. Then $\log(w_{it}) = p_t a_i = x_i(p_t\beta) + p_t u_i$, where p_t is the economywide "price" of skill. Skill-biased technological change in the rising-skill-price view is merely an increase over time in p_t.

15. Juhn, Murphy, and Pierce (1991) argued that blacks tend to have lower levels of unobserved ability characteristics and that rising returns to these characteristics held down relative wages for blacks in the 1980s.

TABLE

Use of Computers at Work (Percent)

	1984	1989	1993	1997
All workers	24.5	36.8	46.0	49.9
By education				
Dropouts	4.8	7.4	8.9	11.3
High school	19.8	29.2	34.0	36.1
Some college	31.9	46.4	53.5	56.3
College (or more)	41.5	57.9	69.1	75.2
High school/college	47.7	50.5	49.1	48.1
By gender				
Men	21.1	31.6	40.3	44.1
Women	29.0	43.2	52.7	56.7
Male/female	73.0	73.2	76.5	77.8
By gender and education				
High-school men	12.9	20.1	24.1	26.8
College men	42.7	58.8	70.5	75.5
High-school women	27.5	39.2	45.1	46.8
College women	39.6	56.6	67.4	74.7
High school/college (men)	30.2	34.2	34.2	35.5
High school/college (women)	69.4	69.3	66.9	62.7
Male/female (high school)	46.9	51.3	53.4	58.3
Male/female (college)	107.8	103.9	104.5	101.1
By race				
Whites	25.3	37.9	47.3	51.3
Blacks	18.2	27.2	36.2	39.9
Other	23.7	36.0	42.3	48.2
Black/white	72.1	71.7	76.7	77.7
By age				
Under 30	24.7	34.9	41.4	44.5
30–39	29.5	42.0	50.5	53.8
40–49	24.6	40.6	51.3	54.9
50 and older	17.6	27.6	38.6	45.3

Notes: Entries display percentage of employed individuals who answer that they "directly use a computer at work" in the October Current Population Survey (CPS) Computer Use Supplements. Samples include all workers with at least one year of potential experience. College workers include those with a college degree or higher education. All tabulations are weighted by CPS sample weights.

relative wages. On the other hand, since older workers earn more than younger workers, the rising-skill-price view of SBTC predicts a rise in age- or experience-related wage premiums over the 1980s and 1990s.

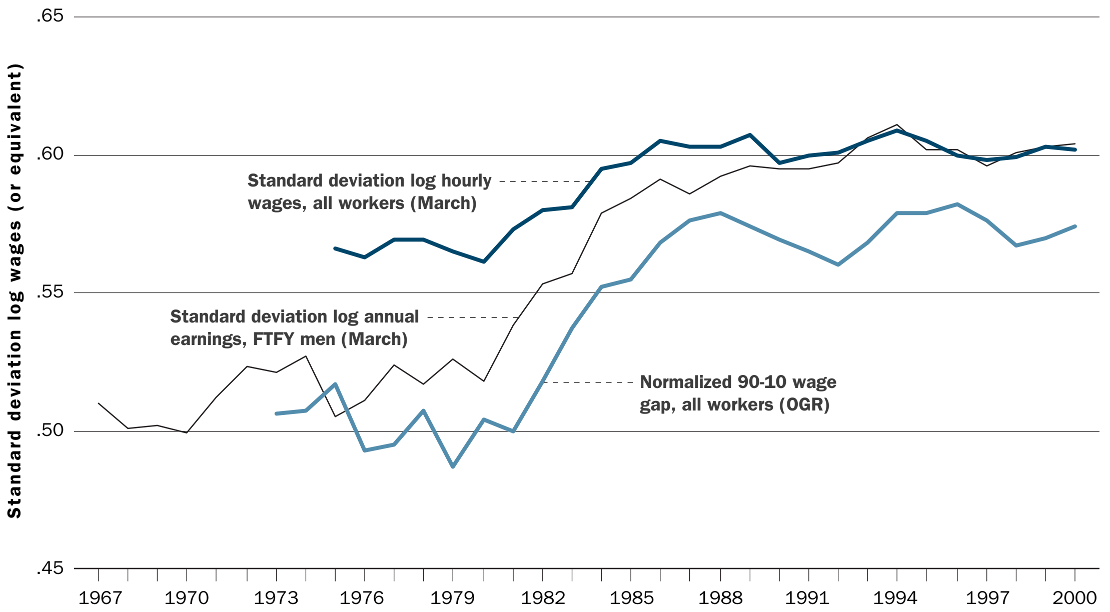
In what follows, we briefly review some important changes in wage inequality and in the wage structure. Throughout we will discuss both problems and puzzles for SBTC. The problems are facts that seem superficially inconsistent with both (either) version of the theory; the puzzles are important developments in the wage structure that are potentially consistent with SBTC but appear to be driven by other causes.

Trends in Overall Wage Inequality

Although measurement of wage inequality is substantially more straightforward than the measurement of technological change, there are a number of potentially important issues. The Current Population Survey (CPS) that is the most widely

CHART 2

Alternative Measures of Aggregate Wage Inequality



Source: Authors' analysis of March, May, and Outgoing Rotation Group files from monthly Current Population Survey and EPI

used source for data on individual wages (and the source we use here), for instance, experienced a substantial redesign in the mid-1990s that appears to have raised measured inequality. Nonetheless, our most important findings appear robust to choice of data sets and a variety of different methodologies for the measurement of inequality.[16]

Chart 2 plots three different measures of aggregate wage dispersion. The first is the standard deviation of log annual earnings for full-time full-year (FTFY) male workers, constructed from March CPS data from 1968 to 2001.[17] The second is the normalized 90-10 log wage gap in hourly earnings, based on the May CPS files for 1973 to 1978 and the OGR files from 1979 onward. This series is based on estimates constructed by the Economic Policy Institute (EPI), using procedures very similar to ours.[18] The third is the standard deviation of log hourly wages for all workers in the March CPS files from 1976 to 2001, weighted by the hours worked in the previous year.

An examination of the chart suggests that the recent history of U.S. wage inequality can be divided into three episodes. During the late 1960s and 1970s, aggregate wage inequality was relatively constant. The standard deviation of log wages for FTFY men rose by only 0.01 between 1967 and 1980 (from 0.51 to 0.52).[19] Wage inequality measures from the May CPS/OGR series also show relative stability (or even a slight decline) between 1973 and 1980 while the hours-weighted standard deviation of log hourly wages for all workers in the March CPS was stable from 1975 to 1980. The 1980s was a period of expanding inequality, with most of the rise occurring early in the decade. Among FTFY men, for example, 85 percent of the 10-point rise in the standard deviation of log wages between 1980 and 1989 occurred before 1985. Finally, in the late 1980s wage inequality appears to have stabilized. Indeed, none of the three series in Chart 2 shows a noticeable change in inequality between 1988 and 2000.

16. Card and DiNardo (2002) discuss at length issues of measurement and the robustness of the findings to alternative data sources and measurement methodologies.

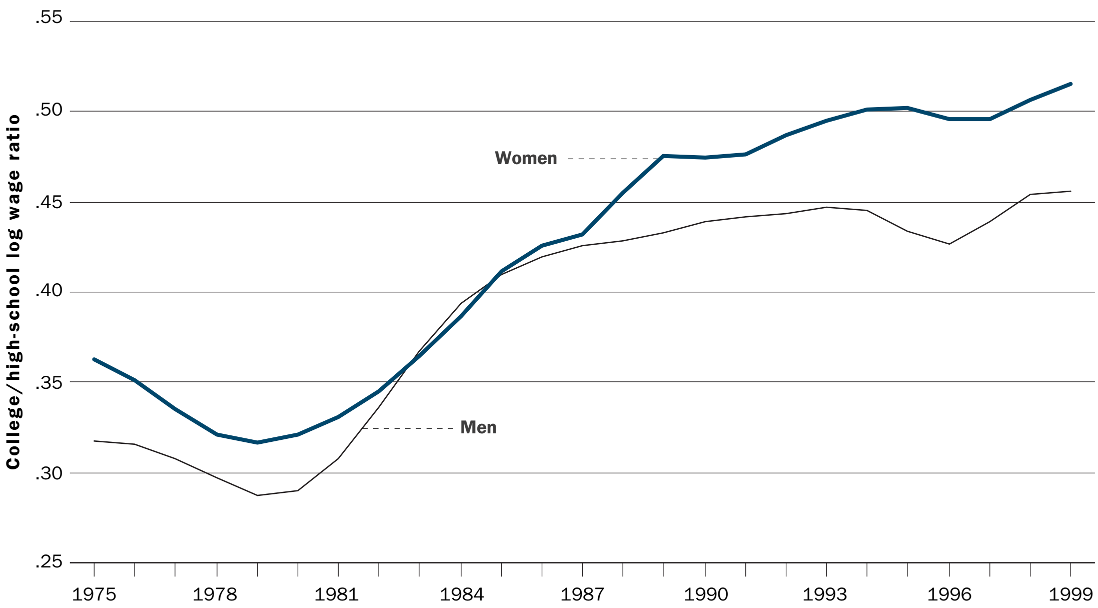
17. Here and in what follows, we refer to the data derived from the March supplement to the CPS as the March CPS and the data from the Outgoing Rotation Group files and the 1973–78 May supplements as the OGR and May CPS data, respectively. See Card and DiNardo (2002) for more details.

18. See Mishel, Bernstein, and Schmitt (2001, table 2.17). For details on this and all other aspects of the data, see Card and DiNardo (2002).

19. Similarly, the standard deviation of log wages for all full-time workers (men and women) was slightly lower in 1980 than in 1967.

CHART 3

College/High-School Wage Ratio by Gender, 1975–99



Source: Authors' analysis of March Current Population Survey, various years

The apparent stability of aggregate wage inequality over the 1990s presents a potentially important puzzle for the SBTC hypothesis, since there were continuing advances in computer-related technology throughout the decade that were arguably as skill biased as the innovations in the early 1980s.

Another interesting feature of the series in Chart 2 is that the rise in wage inequality over the 1980s was larger for FTFY men than for workers as a whole. While the reasons for this are unclear, if viewed with an eye toward SBTC, the relative rise in inequality for FTFY men is a puzzle. To the extent that SBTC tends to widen inequality across skill and ability groups, we would expect to see a larger rise in inequality for less homogeneous samples (for example, pooled samples of men and women and full- and part-time workers) and a smaller rise for more homogeneous samples (such as FTFY men). The data suggest the opposite.[20]

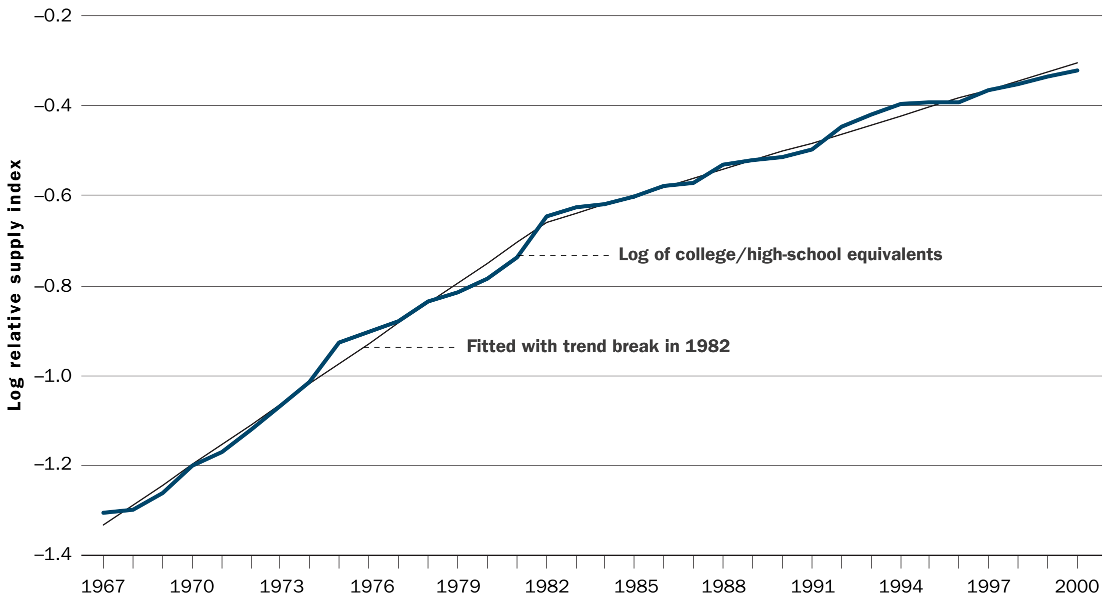
Components of the Wage Structure

Returns to college. We now shift our focus to specific dimensions of the wage structure. We begin with wage differences by education, which are at the core of the SBTC hypothesis. Chart 3 presents estimates of the college/high-school wage gap by gender for the 1975–99 period, based on average hourly earnings data from the March CPS.[21] Trends in the college/high-school gap are similar to the trends in overall inequality and suggest three distinct episodes: the 1970s, when the college gap was declining slightly; the 1980s, when the gap rose quickly; and the 1990s, when the gap was stable or rising slightly. For both men and women, the college/high-school wage gap rose by about 0.15 log points between 1980 and 1990. The rise for men was concentrated in the 1980–85 period while for women it was more evenly distributed over the decade. The similar overall rise in returns to college for men and women is interesting, however, because as noted earlier there is a much larger education gradient in computer use rates for men than women. Based on this fact, the computer-complementarity version of the SBTC hypothesis would predict a larger rise in the college/high-school wage gap for men than for women during the 1980s and 1990s. On the other hand, since the college/high-school wage gaps are similar for men and women, the skill-price version of SBTC predicts about the same rise in returns for both. Thus, the similarity of the rise in the college gap for men and women is a puzzle for one version of the theory but not for the other.

Some previous authors have argued that variation in the college/high-school wage premium can be explained by a model like equation 2, with the added assumption that the effect of changing technology follows a smooth trend (see, for example, Freeman 1975 and Katz and Murphy 1992). In these

CHART 4

Relative Supply of College-Educated Labor



Source: Authors' analysis of the March Current Population Survey, various years. See Card and DiNardo (2002) for details.

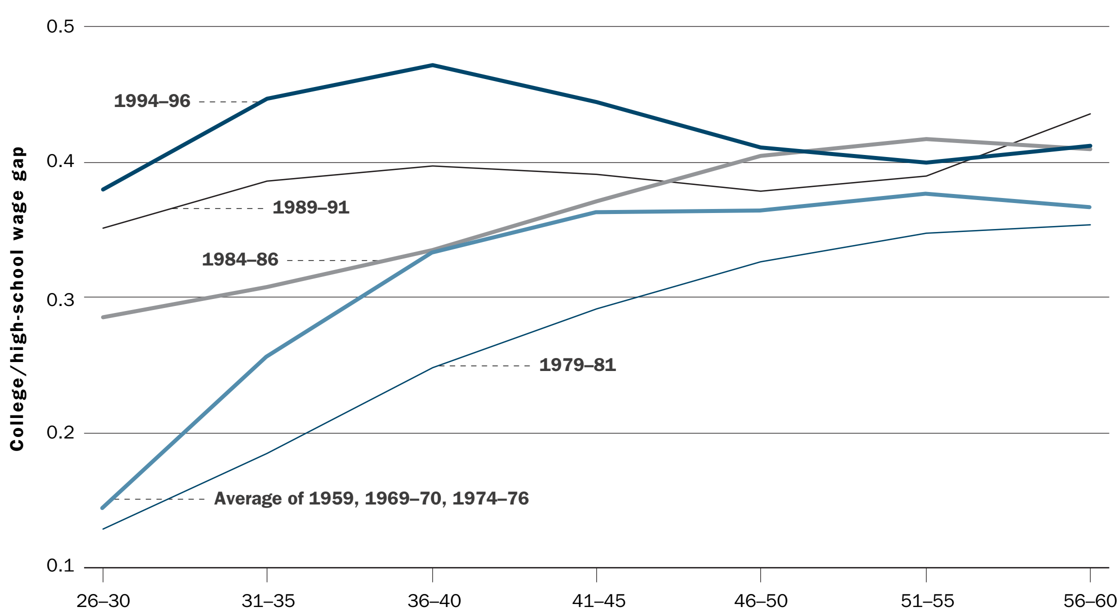
studies the relative supply of college workers is estimated by assigning various fractions of "college-equivalent" and "high-school-equivalent" labor units to workers in different education categories.[22] Using a variant of this method, we derive such a supply index, which is displayed in Chart 4. A feature of this index—which is revealing about a potential problem with the SBTC hypothesis—is that it follows a roughly constant trend between 1967 and 1982 (4.5 percent per year) and a slower but again nearly constant trend after 1982 (2.0 percent per year).[23] Assuming that $1/\sigma$ is positive, shifting trends in relative supply can potentially explain an upward shift in the rate of growth of the college/high-school wage gap in the early 1980s but not the slowdown in the 1990s.

The problem is further revealed by comparing estimates of models based on equation 2 that exclude or include the 1990s. For example, augmenting the model with a trend shift term that allows for a possible acceleration in SBTC after 1980, the estimate of the relative supply term becomes wrong-signed, and the model substantially overpredicts returns to college in the late 1990s.[24] We conclude that the slowdown in the rate of growth in the return to college in the 1990s is a problem for the SBTC hypothesis that cannot be easily reconciled by shifts in relative supply.

20. As we explain in the longer version of this paper, although we prefer to measure aggregate wage inequality using the broadest possible sample of workers, the tradition in the inequality literature has been to analyze men and women separately (although Lee 1999 and Fortin and Lemieux 2000 are important counterexamples). Treating men and women separately, however, yields substantially the same conclusions for men. For women the trends in inequality are a little different although they pose essentially the same problems for SBTC. For instance, whether the OGR or March data are used, it is clear that most of the rise in gender-specific wage inequality, like the rise in overall inequality, was concentrated in the first half of the 1980s, with surprisingly little change in the 1990s.
21. These estimates are obtained from regression models fit separately by gender and year to samples of people with either twelve or sixteen years of education. The models include a dummy for college education, a cubic in years of potential experience, and a dummy for nonwhite race.
22. For example, a worker with fourteen years of education contributes one-half unit of college labor and one-half unit of high-school labor while a worker with ten years of education contributes something less than one unit of high-school labor.
23. Indeed, a regression of the supply index on a linear trend and post-1982 trend interaction yields an R^2 of 0.997.
24. See Card and DiNardo (2002.) Beaudry and Green (2002) experiment with several variants of equation 2 and report similar findings.

CHART 5

Changing Age Structure of the College/High-School Wage Gap



Source: Card and Lemieux (2001)

Education and age. So far we have focused on the average difference in wages between college and high-school workers in all age groups. This focus arises naturally out of a model such as the one described by equations 1 and 2, where there are only two skill groups—high and low education—and workers with different years of labor market experience are treated as perfect substitutes. In such a model, there is a unique "return to education" in the economy as a whole at any point in time. Moreover, the focus on average returns to college is descriptively adequate whenever the wage differentials between education groups are the same for people with different ages or different years of experience, as in Mincer's (1974) human capital earnings function.[25]

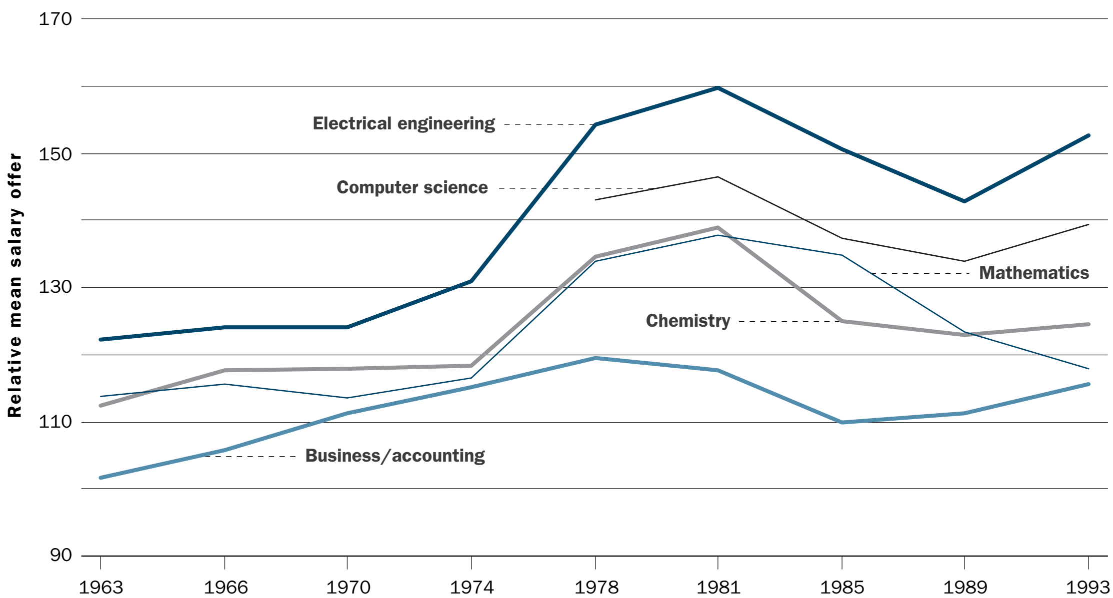
While the rise in the average wage gap between college and high-school workers has been extensively documented, the fact that the increases have been very different for different age groups is less well known. Specifically, the rise in the college/high-school wage gap for men is most pronounced among young workers entering the labor force after the late 1970s. Moreover, the pattern of this increase does not appear to be well explained by either the rising-skill-price or computer-use/skill complementarity versions of SBTC.

One assumption embedded in equation 1 is that workers with similar educations but different ages are perfect substitutes in production. Card and Lemieux (2001) show that one implication of a more general model that allows for imperfect substitution across age groups is the presence of cohort effects in the returns structure. Because education is (essentially) fixed once a cohort enters the labor market, a cohort with fewer highly educated workers will experience higher relative returns at each age, leading to cohort-specific deviations from the average pattern. Evidence of such cohort effects is presented in Chart 5 (taken from Card and Lemieux 2001), which shows the age profiles of the college/high-school wage gap for five-year age cohorts of men in five periods: 1960–76 (based on pooled data from the 1960 Census and early CPS surveys), 1979–81, 1984–86, 1989–91, and 1994–96. In the 1960s and early 1970s the college/high-school wage gap was an increasing and slightly concave function of age, consistent with the functional form posited by Mincer (1974). Subsequent changes in the age structure of the college/high-school gap, however, reveal a "twisting" of the age profile—large increases in the gap at relatively young ages during the mid-1980s to the mid-1990s and relatively small changes in the gap for older men.

Based on the data in Chart 5 and a series of formal statistical tests, Card and Lemieux (2001) argue that the trends in the college/high-school wage gap for different age groups reflect systematically higher college/high-school wage premiums received by successive cohorts that have entered the labor market since the late 1970s. Moreover, these cohort effects

CHART 6

Mean Salary Offer Relative to Humanities/Social Sciences



Source: Authors' analysis of data from National Association of Colleges and Employers

are highly correlated with cohort-specific changes in the relative supply of college workers. Somewhat surprisingly, after controlling for cohort-specific supplies, they find that the return to education was about the same in the mid-1990s as it had been in the mid-1970s. This interpretation of the data leaves little or no room for accelerating technical change; while one could argue that the spread of computers led to cohort-specific relative productivity gains for college-educated workers, there is no direct evidence of such a phenomenon. Moreover, the age profiles of the college/high-school gap in computer use shifted uniformly between 1984 and 1997, rather than twisting like the returns profiles in Chart 5.

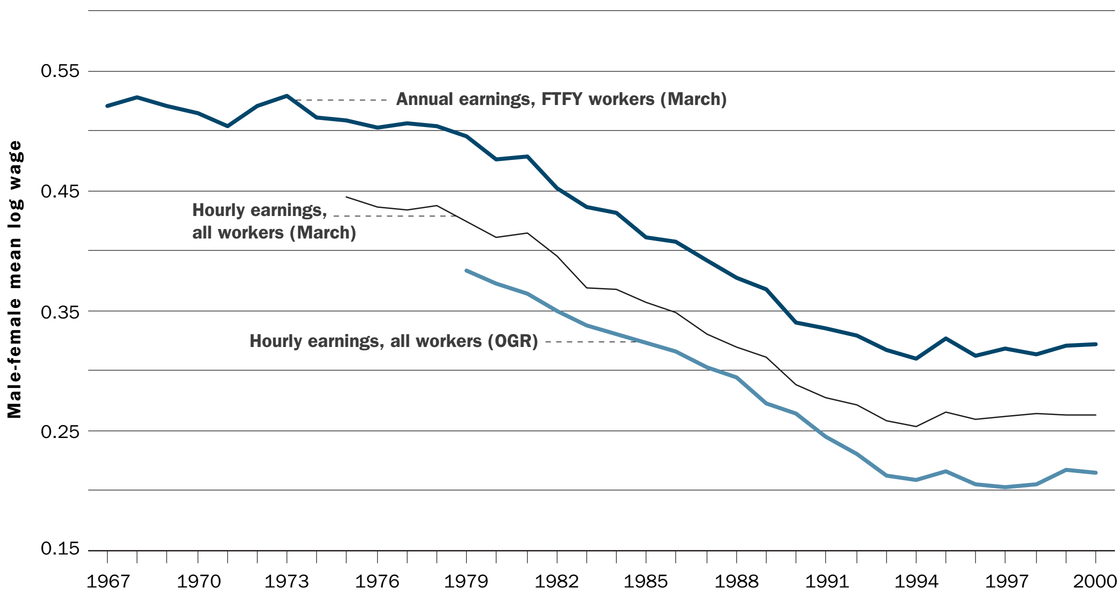
Returns to different college degrees. One concern with evidence for SBTC based on overall wage differences between college and high-school workers is that computer-related technology may have had different effects on college graduates from different fields of study. In particular, it seems plausible that the computer revolution would lead to a rise in the relative demand for college graduates with more "technical" skills (like engineers and scientists), especially in the early 1980s when microcomputers were first introduced and the college/high-school wage gap was expanding rapidly. Chart 6 displays mean starting salaries offered to graduating students with bachelors degrees in various fields, compiled from a survey of career placement offices conducted by the National Association of Colleges and Employers, and brings some evidence to bear on this possibility.[26] For convenience, we have scaled the data to show mean salaries relative to humanities and social sciences. The most obvious feature of the data is that the relative salaries in more technical fields rose in the 1970s and fell in the 1980s. This pattern is particularly true for the relative salaries in the two fields most closely connected with computers: computer science and electrical engineering. Paradoxically, the introduction of microcomputers was associated with a fall in the relative salaries of specialized college graduates with the strongest computer skills. Although the data in Chart 6 cover only the period up to 1993, more recent data suggest that in the late 1990s the relative salaries of electrical engineering and computer

25. The simplest way to justify Mincer's formulation within the framework of the model in equation 1 is to assume that the relative efficiency units of different age groups depend only on experience (for example, age minus education) and that the relative efficiency profile is the same for college and high-school labor.

26. An alternative data source on college graduates' relative salaries in different fields, the Recent College Graduates Survey (which is available only since 1977), shows similar patterns. See U.S. Department of Education (1998, supp. table 33-1).

CHART 7

Male-Female Wage Gaps



Source: Authors' analysis of March and May Current Population Survey, various years, and Outgoing Rotation Group files from monthly Current Population Survey, various years

science graduates rose back to the levels of the late 1970s. Thus, the IT-sector boom in the late 1990s was associated with a rise in relative wages of graduates with computer-related skills.

We regard the trends in the relative salaries of college graduates in different fields as at least a puzzle, if not a problem, for the SBTC hypothesis. While innovations in computer technology do not necessarily raise the relative demand for workers with the most specialized computer training, engineers and computer scientists have very high rates of computer use and also earn higher wages than other bachelor degree holders. Thus, the decline in the wage premium for engineers and computer science graduates over the 1980s is inconsistent with either the computer-use/skill-complementarity or rising-skill-price versions of the SBTC hypothesis.

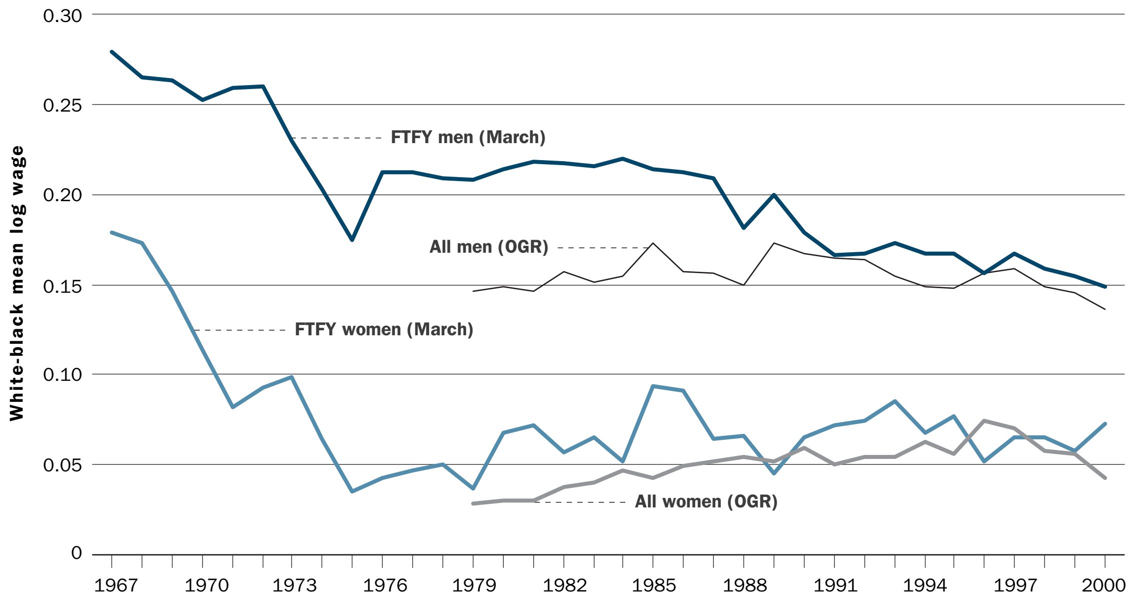
Other Changes in the Structure of Wages

The male-female wage gap. One of the most prominent changes in the U.S. wage structure is the recent closing of the male-female gap. Chart 7 displays three estimates of the gap in wages between men and women: the difference in mean log annual earnings of full-time/full-year workers (based on March CPS data); the difference in mean log average hourly earnings from the March CPS (for 1975 and later); and the difference in mean log average hourly earnings from the OGR supplements (for 1979 and later). Like overall inequality and returns to college, trends in the male-female wage gap seem to fall into three distinct episodes. During the 1970s, the gender gap was relatively stable. During the 1980s and early 1990s the gap fell. Finally, in the mid- to late-1990s the gap was stable again. Although the different wage series give somewhat different estimates of the size of the gender gap, all three show a 15 percentage point decline between 1980 and 1992. Moreover, these trends are very similar for different age and education groups.

These trends, and their similarity for different age and education groups, pose a number of problems and puzzles for different versions of the SBTC hypothesis. As noted earlier, the closing of the gender gap in the 1980s is a particular problem for the rising-skill-price version of SBTC, which predicts that technological change raises the return to all different kinds of skills, including the unobserved skills that are usually hypothesized to explain the gender gap. Since women use computers on the job more than men, some observers have argued that the decline in the gender wage gap *is* consistent with the computer-use/skill-complementarity version of SBTC.[27] This theory cannot explain the similarity of the trends in the gender gap for high-school and college graduates, however, since college-educated women are actually less likely to use a computer than college-educated men. Thus, like Blau and Kahn

CHART 8

White-Black Wage Gaps



Source: Authors' analysis of March and May Current Population Survey, various years, and Outgoing Rotation Group files from monthly Current Population Survey, various years

(1997), we conclude that the rise in women's wages relative to men's wages over the 1980s must be attributed to gender-specific factors.

The black-white wage gap. Chart 8 shows the evolution of another important dimension of wage inequality—the difference in wages between white and black workers. The chart shows the wage gaps for full-time/full-year men and women (derived from March CPS data) and for all men and women (based on average hourly earnings from the OGR data). The gaps for women are similar whether the data are confined to FTFY workers or not while the gaps for men are slightly different between FTFY workers and all workers, at least in the early 1980s. As previous studies have documented, racial wage gaps are also much smaller for women than for men. More interesting from our perspective are the trends in the racial wage gap, which are quite different from the trends in other dimensions of inequality. During the 1970s, when the gender gap and overall wage inequality were relatively stable, the wage advantage of white workers fell sharply: from 28 to 18 percent for men and from 18 percent to 4 percent for women. During the 1980s, when overall wage inequality was rising and the gender gap was closing, the black-white wage gap was relatively stable. Finally, over the 1990s, racial wage gaps were roughly constant. The gaps for high-school and college-educated men and women are similar to the corresponding gaps for all education groups and follow roughly similar trends.

Like the gender wage gap, we view the evolution of racial wage differences as at least a puzzle, and potentially a problem, for SBTC. Both the rising-skill-price view and the computer-use/skill-complementarity view suggest that SBTC should have led to a widening of racial wage gaps in the 1980s. The gap in computer use between blacks and whites is about the same magnitude as the male-female gap, so the same arguments that have been made about the effect of computerization on male-female wage differences would seem to apply to race. Indeed, Hamilton (1997) argues that a computer skills gap contributed to an increase in the wage differentials between whites and blacks. In view of the data in Chart 8, however, it is clear that other factors must have worked in the opposite direction to offset any such effects of SBTC.

Work experience. Along with education, gender, and race, a fourth key dimension of wage inequality in the U.S. labor market is age. Following Mincer (1974), most labor market analysts have adopted the

27. For example, Weinberg (2000) argues that "since computer [jobs] are likely to be less physically demanding than the average noncomputer job, the elimination of noncomputer jobs in which men have a comparative advantage and the creation of computer jobs in which women have a comparative advantage would tend to favor women."

assumption that log wages are a separable function of education and potential labor market experience (age minus education minus 6): In this framework, if there is an increase in the return to skill caused by changes in technology, we should expect the return to an additional year of experience to rise. As shown in more detail in Card and DiNardo (2002), here too the evidence is not favorable for SBTC. For example, there is little evidence of either a rise or fall in the average return to experience over the period 1979 to 1991 for high-school-educated men, who make up about one-third of all male workers. Much the same is true for younger college-educated men (those between the ages of twenty-four and thirty-seven who have two to fifteen years of potential experience), and for college-educated men in the middle range of experience, the wage profile actually became flatter over the 1980s and 1990s.

Given this analysis of the change (or lack of change) in men's experience profile, it is difficult to rationalize the somewhat different evolution of the potential experience profile for women in an SBTC framework. During the period 1979–91, experience profiles did become somewhat steeper for both high-school- and college-educated women, particularly for women with between two and eighteen years of potential experience. Manning (2001) has shown that for women in the United Kingdom, where the male-female wage gap also closed substantially over the 1980s, a similar increase in the returns to experience can be in part explained by a shift across cohorts in the fraction of time spent working.[28] How far such an analysis could go toward explaining the these shifts in the experience profile is an interesting question. In any case, we suspect that SBTC has little to do with the story.

Residual inequality. SBTC has also been proposed as an explanation for the rise in inequality among workers with similar observable characteristics. To the extent that wage differences between workers with the same education, age, gender, and race reflect the labor market's valuation of unmeasured productivity, the rising-skill-price version of SBTC predicts a rise in the residual variance associated with a standard human capital model of wage determination while the prediction from the computer-complimentarity version of SBTC is unclear. As documented in Card and DiNardo (2002), however, the trends in residual inequality pose much the same difficulties as the trends in overall inequality that we have documented here. In particular, we find that most of the modest rise in residual inequality was concentrated in the early 1980s, which suggests that if SBTC is the cause for this change, it occurred during the earliest years of the microcomputer revolution.

SBTC and Productivity

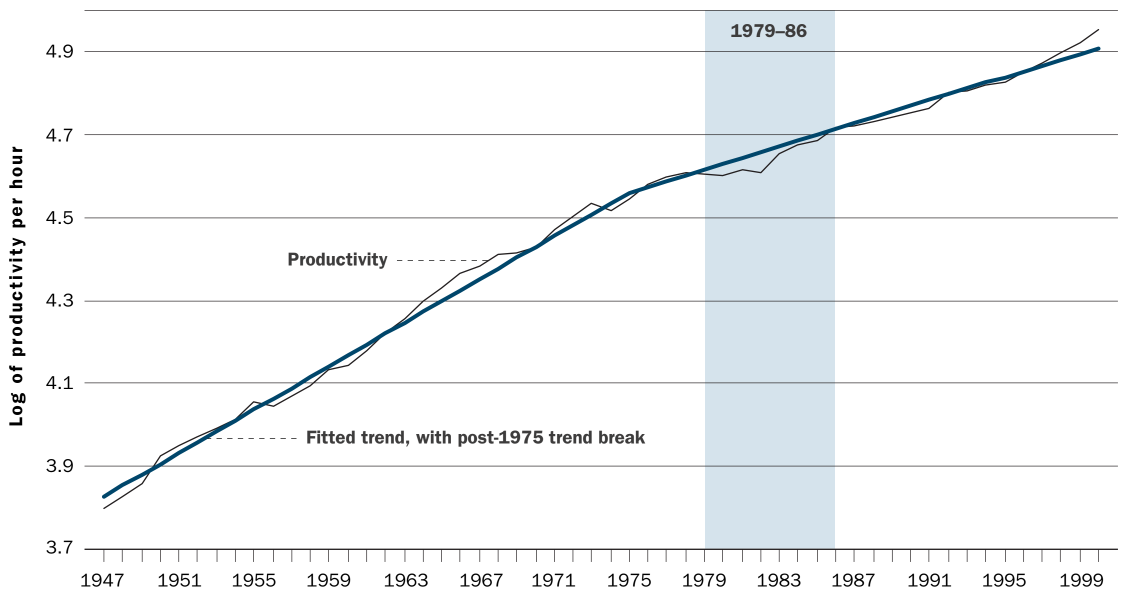
A final issue worth discussing is the relationship between SBTC and productivity growth. Many analysts have noted that the pace of aggregate productivity growth was stable during the 1980s and early 1990s despite the introduction of computers and the almost immediate effect that computerization is presumed to have had on wage inequality.[29] To illustrate, Chart 9 plots the log of real output per hour in the nonfarm business sector of the United States over the 1947–2000 period, along with a fitted trend line that allows a productivity slowdown after 1975.[30] The rate of labor productivity growth during the 1980s and early 1990s was substantially slower than in 1947–75. However, between 1979 and 1986, when aggregate wage inequality was expanding rapidly, productivity first fell relative to trend (during the 1980 and 1982–83 recessions), then recovered to its earlier trend level. There is no indication that developments in the early 1980s led to an unexpected change in the productive capacity of the economy.

We regard the absence of a link between SBTC (as measured by the rate of increase in wage inequality) and aggregate productivity growth as a puzzle, although not necessarily a problem, for SBTC. While some theoretical discussions of technological change assume that any new technology leads to an outward shift in the economywide production frontier, some specific versions of SBTC do not. Extensive SBTC—a rise in the share parameter α in the aggregate production function given in equation 1 that would raise the productivity of some workers and lower that of others—would be consistent with rising wage inequality but not necessarily raising aggregate labor productivity. Nonetheless, it is rather surprising that whatever shifts in technology led to the rapid growth in inequality between 1980 and 1985 appeared to have no effect on the trend in aggregate productivity.

In comparison to the early 1980s, the late 1990s may turn out to be a better example of a period of rapid technologically driven output growth. As shown in Chart 9, aggregate output growth was considerably above trend in the 1998–2000 period. Moreover, some (but not all) measures of wage inequality show a rise after 1995 or 1996. Some detailed microlevel analyses point to specific technology-related changes in workplace organization that have a significant impact on productivity (see, for example, Bresnahan, Brynjolfsson, and Hitt 2002). In view of the confounding effect of the extraordinary business cycle

CHART 9

Trends in Productivity per Hour, Nonfarm Business Sector



Source: Authors' analysis of Bureau of Labor Statistics data (see footnote 30)

conditions during the late 1990s, however, it may be some time before a definitive interpretation of this period is reached.

Conclusion

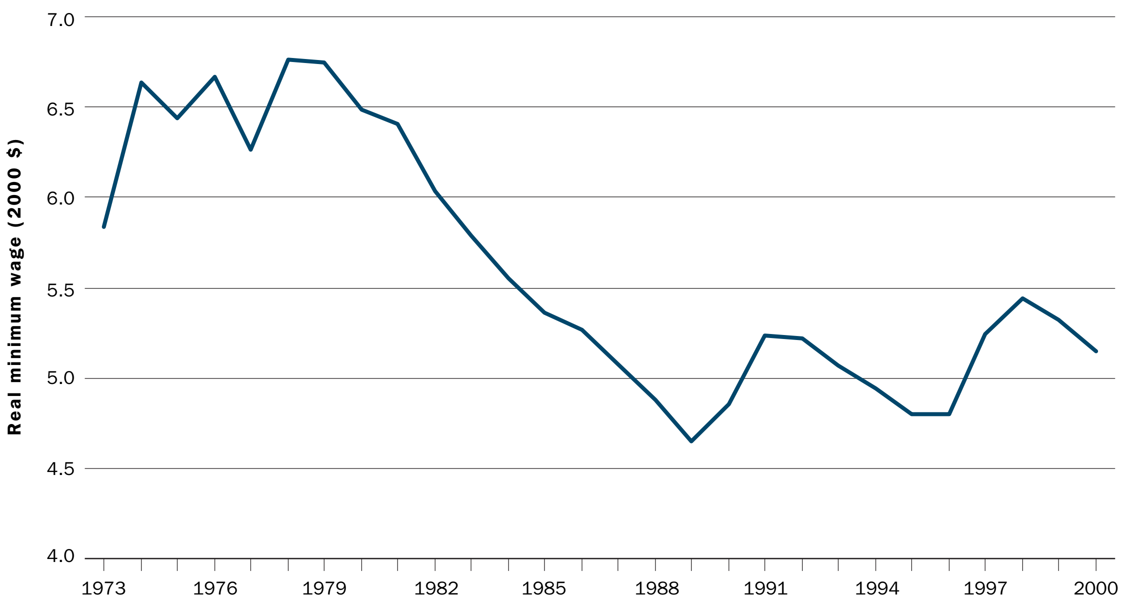
What is one to make of recent trends in wage inequality and productivity and the links (or absence of links) to computer-related technology? From the vantage point of an analyst looking at the available data in the mid- to late 1980s, there were many reasons to find skill-biased technological change a plausible explanation for the large increase in inequality that began in the early 1980s. First and foremost, the timing seemed right. During the 1970s, the college/high-school wage gap narrowed. Richard Freeman's 1976 book *The Overeducated American* argued that the U.S. labor market suffered from an oversupply of educated workers. By 1985 the situation had clearly reversed, and education-related wage gaps and other dimensions of wage inequality were on the rise. At the same time, the personal computer was making dramatic inroads into the workplace, the stock market valuation of technology firms was rising, and articles in the business press were expounding the effects of the new technology. Analysts in the late 1980s had no way of knowing that, although computer use would continue to expand over the next decade and the stock market value of technology firms would rise, the increase in wage inequality was largely over.

Viewed from 2002, the rise in wage inequality now appears to have been an episodic event. Of the 17 percent rise in the 90-10 wage gap between 1979 and 1999 for all workers in the OGR wage series (see Chart 2), 13 percentage points (or 76 percent) occurred by 1984, the year that the IBM-AT was introduced. While some of the early rise in inequality may have been due to rapid technological change, we suspect that the increase in the early 1980s is

28. To the extent that the measured potential experience profile reflects the relationship between wages and actual experience, for example, such a shift in the labor force participation rates of women would cause a steepening of the wage/potential experience profile.
29. For example, in a 1996 statement Alan Greenspan observed that "the advent of the semiconductor, the microprocessor, the computer, and the satellite . . . has puzzled many of us in that the growth of output as customarily measured has not evidenced a corresponding pickup" (quoted in McGuckin, Stiroh, and van Ark 1997).
30. The productivity series is series PRS85006093, from the U.S. Bureau of Labor Statistics, uploaded December 2001. The fitted trend in the log of output per hour is 0.0262 in the period 1947–75 and 0.0139 in the period 1976–2000.

CHART 10

Real Minimum Wage, 1973–2000



Source: Authors' analysis. See also <www.dol.gov/esa/minwage/chart.htm>.

largely explained by other plausible—albeit relatively mundane—factors. A primary candidate is the fall in the real value of the minimum wage. In 1979 the modal wage for women with a high-school education was $2.90 an hour—the level of the federal minimum wage (DiNardo, Fortin, and Lemieux 1996). Over the next five years the consumer price index rose by 48 percent while the minimum wage increased by only 15 percent, leading to a steep decline in the influence of the minimum wage on the lower tail of the wage distribution. Chart 10 plots the real value of the federal minimum wage between 1973 and 2000. Examination of this figure suggests that it is nearly a mirror image of the inequality series in Chart 2. Indeed, as shown in Chart 11, predictions from a simple regression of the normalized 90-10 wage gap (from the May CPS and OGR data) on the log of the real minimum wage track the actual wage gap very closely. This simple model explains over 90 percent of the variation in the 90-10 wage gap and captures many of the key turning points.

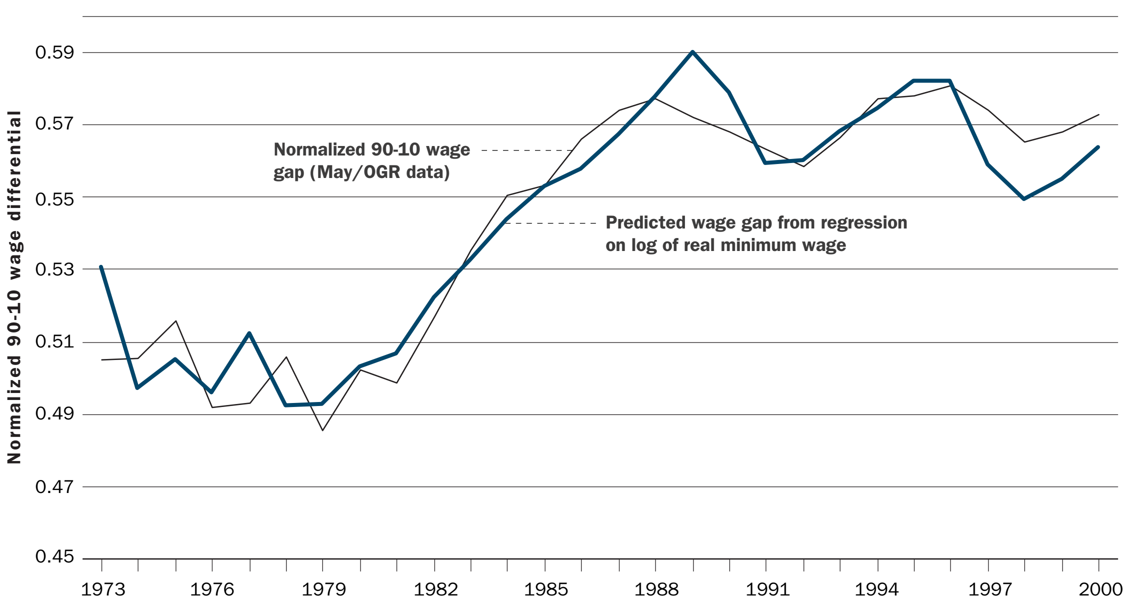
Of course, neither this informal analysis nor the more exhaustive study by Lee (1999) imply that the minimum wage can explain *all* the changes in the wage structure that occurred in the 1980s and 1990s. Indeed, we have documented several important changes that cannot be explained by the minimum wage, including the closing of the gender gap.[31] Nevertheless, we suspect that trends in the minimum wage and other factors such as declining unionization and the reallocation of labor caused by the 1982 recession can help to explain the rapid rise in overall wage inequality in the early 1980s.

Overall, the evidence linking rising wage inequality to skill-biased technological change is surprisingly weak. Moreover, we conjecture that a narrow focus on technology has diverted attention away from many interesting developments in the wage structure that cannot be easily explained by skill-biased technological change. Perhaps the perspective of a new decade will help to open the field of unexplained variance to all players.

31. Lee (1999) presents a detailed cross-state evaluation of the effect of the minimum wage on overall wage inequality and concludes that the fall in the real minimum wage can explain nearly all the rise in aggregate inequality in the 1980s. That the minimum wage explains most of the change in overall inequality, but cannot explain specific changes in the wage structure, is not as puzzling as it might first appear. Fortin and Lemieux (1998, 2000) show that although the 1980s saw very large increases in gender-specific wage inequality, changes in the overall distribution of wages were much smaller. Lee's analysis suggests that these are largely explainable by the minimum wage.

CHART 11

Wage Inequality and the Minimum Wage



Source: Authors' analysis of various May and Outgoing Rotation Group files from monthly Current Population Survey and EPI. See also <www.dol.gov/esa/minwage/chart.htm>.

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