TECHNOLOGICAL CHANGE, COMPUTERIZATION, AND THE WAGE STRUCTURE

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Overall wage inequality and educational wage differentials have expanded substantially in the United States over the past two decades. This widening of the wage structure has coincided with the rapid computerization of the work place. Thus, it is not surprising that many labor market analysts have tried to draw a causal connection between rising earnings inequality and increases in growth rate of the relative demand for more-skilled workers driven by technological and organizational changes associated with the computer revolution (e.g., Bound and Johnson 1992; Krueger 1993). Such inferences follow a venerable and fruitful tradition extending back to Paul Douglas (1926) and Jan Tinbergen (1975) of viewing the evolution of the wage structure (at least partially) as depending on a race between technological development and educational advance. This hypothesis implies that improvements in access to post-secondary schooling and appropriate skills training may be necessary to allow the productivity benefits of the new technologies associated with the digital economy to be more widely shared.

Two key pieces of evidence are often cited as being strongly suggestive of an integral role for skill-biased technological change in the recent rise in U.S. wage inequality.[1] The first is that the relative employment of more-educated workers and non-production workers has increased rapidly within detailed industries and within establishments in the United States during the 1980s and 1990s, despite the sharp rise in the relative wages of these groups (Autor, Katz, and Krueger 1998; Lawrence and Slaughter 1993; Dunne, Haltiwanger, and Troske 1996). This pattern indicates strong within-industry demand shifts favoring the more skilled. Similar patterns of within-industry increases in the proportion of “skilled” workers are apparent in most other advanced nations (Berman, Bound,

[1] Skill-biased technological change refers to any introduction of a new technology, change in production methods, or change in the organization of work that increases the demand for more-skilled labor (e.g., college graduates) relative to less-skilled labor (e.g., non-college workers) at fixed relative wages.

and Machin 1998; Machin and Van Reenen 1998). Skill-biased technological change (broadly interpreted to be associated with both new production technologies and organizational innovations) is a natural possibility for such unexplained within-sector growth in the demand for skill.[2]

The second more direct evidence from both econometric and case-study research is that the relative utilization of more-skilled workers is strongly positively correlated with capital intensity and the introduction of new technologies (Bartel and Lichtenberg 1987; Doms, Dunne, and Troske 1997; Levy and Murnane 1996). These findings imply that physical capital and new technologies are relative complements with more-skilled workers. Such evidence is certainly consistent with the view that the spread of computer technologies may have contributed to rapid increases in the demand for skill in recent decades.

Nevertheless, similar evidence of capital-skill complementarity and rapid skill-biased technological advance is apparent throughout the twentieth century even in periods of stable or narrowing educational and occupational wage differentials. For example, Goldin and Katz (1998) find that capital-deepening, the diffusion of technologies using purchased electricity, and the introduction of continuous-process and batch production methods in manufacturing greatly increased the relative demand for white collar workers and more-educated production workers from 1909 to 1929, but wage differentials by skill actually narrowed during this period. Goldin and Katz (1995, 1999) present evidence indicating that the rapid increase in the supply of skills arising from the high school movement prevented a rise in wage inequality during the skill-biased technological revolution associated with the electrification of the work place. Longer-term historical comparisons of changes

[2] Foreign outsourcing of less-skilled jobs is another possible explanation for this pattern (Feenstra and Hanson 1999). But large within-industry shifts towards more skilled workers are pervasive even in sectors with little or no observed foreign outsourcing activity.

in technology, the demand for and supply of skills, and wage inequality are necessary to properly assess the labor market impacts of computerization and the digital economy.

Although technological advance has contributed substantially to secular increases in the demand for skill over the last century, it is less clear that the large increase in wage inequality of the last two decades necessarily implies acceleration in the pace of demand shifts against less-skilled workers arising from the computer revolution. A slowdown in the rate of growth of the relative supply of more-educated workers from the 1970s to the 1980s may have been an important factor (Katz and Murphy 1992; Murphy and Welch 1992). And much work suggests that changes in pay-setting norms and labor market institutions (e.g., declining union strength and an erosion of the value of the minimum wage in the 1980s) also contributed to the magnitude of recent increases in U.S. wage inequality (DiNardo, Fortin, and Lemieux 1996).

This paper assesses the burgeoning literature on the role of the spread of computers and computer-based technologies on changes in the demand for skill and wage inequality over the past two decades.[3] Section I summarizes the nature and magnitude of recent changes in the U.S. wage structure. Section II places these changes into a longer-term historical perspective and examines the evolution of the wage structure and the relative demand and supply for skills from 1940 to 1998. Sharp secular increases in the relative demand for more-educated workers are apparent since 1950 with evidence of some acceleration such demand shifts with the spread of computers in the 1980s and some slowdown with the evolution of the digital economy in the 1990s. Section III more directly examines the evidence on the spread of computers in the work place and estimates of the impacts of

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[3] See Autor, Katz, and Krueger (1998) and Bresnahan (1999) for more detailed and technical treatments of these issues.

new computer technologies on the relative demands for different types of workers. Much research consistently finds that increases in the growth of the demand for more-educated workers are concentrated in the most computer-intensive sectors of the economy over the past two decades. But the extent to which this relationship represents a causal effect of computerization on skill demands is difficult to convincingly evaluate. Section IV concludes and speculates on new data collection strategies and empirical approaches designed to improve our understanding of the labor market consequences of the digital economy.

I. Recent Changes in the U.S. Wage Structure

Disparities in the economic fortunes of American families -- as measured by income, consumption, and wealth -- have increased significantly over the past twenty-five years. Economic inequality in terms of wages, family income, and wealth reached higher levels in the mid-1990s than in any time in (at least) the past sixty years (Goldin and Katz, 1999; Wolff 1995, 1998). Labor market changes that have greatly increased overall wage dispersion and shifted wage and employment opportunities in favor of the more educated and more skilled have played an integral role in this process. Many researchers using a variety of data sets -- including both household and establishment surveys -- have documented these changes and found that wage inequality and skill differentials increased sharply in the United States from the late 1970s to the mid-1990s.[4] While much debate exists concerning the causes of changes in the wage structure and earnings inequality, there exists substantial agreement on the "facts" that need to be explained.

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[4] See Katz and Autor (1999) and Levy and Murnane (1992) for reviews of the literature on U.S. wage structure changes and for more detailed references; see Gottschalk and Smeeding (1997) for comparisons of wage structure changes among OECD countries.

Recent changes in the U.S. wage structure can be summarized as follows:

- From the 1970s to the mid-1990s wage dispersion increased dramatically for both men and women. The weekly earnings of a full-time, full-year worker in the 90th percentile of the U.S. earnings distribution (someone whose earnings exceeded those of 90% of all workers) relative to a worker in the 10th percentile (someone whose earnings exceeded those of just 10% of all workers) grew by approximately 45 percent for men and 35 percent for women from 1971 to 1995. Earnings inequality increased even more dramatically if one includes the very top end (top 1 percent) of the distribution. This pattern of rising wage inequality was *not* offset and actually appears to have been *reinforced* by changes in working conditions and non-wage compensation (Hamermesh 1999; Pierce 1999). Recent evidence indicates that the U.S. structure narrowed slightly from 1996 to 1998 (Bernstein and Mishel 1999).

- Wage differentials by education and occupation increased. The labor market returns to years of formal schooling, work-place training, and computer skills appear to have increased in the 1980s and early 1990s. The earnings of young college graduates increased by 33 percent relative to those of young high school graduates from 1979 to 1995. Wage differentials by age (experience) have expanded for non-college workers. But gender wage differentials have narrowed sharply since 1979.

- Wage dispersion expanded within demographic and skill groups. The wages of individuals of the same age, education, sex, and those working in the same industry and occupation, are much more unequal today than twenty-five years ago.

- Increased cross-sectional earnings inequality has not been offset by increased earnings mobility.[5] Permanent and transitory components of earnings variation have risen by similar amounts (Gottschalk and Moffitt 1994). This implies that year-to-year earnings instability has also increased.

- Since these wage structure changes have occurred in a period of sluggish mean real wage growth (deflating wages by official consumer price indices), the real earnings of less-educated and lower-paid workers appear to have declined relative to those of analogous workers two decades ago. The employment rates of less-educated and minority males fell substantially from the early 1970s to the early 1990s (Murphy and Topel 1997). The real wages and employment rates for disadvantaged workers have started to improve over the past few years.

The rise in U.S. wage dispersion has involved both large increases in educational wage differentials and a sharp growth in within-group (or residual) wage inequality. The overall spreading

[5] Earnings mobility measures how individuals move in the earnings distribution between two points in time. The greater the extent of earnings mobility, the greater the likelihood an individual will move among various parts of the distribution over time.

out of the U.S. wage distribution for men and women from 1971 to 1995 is illustrated in Figure 1 using data on real weekly wages of full-time, full-year workers from the March Current Population Survey (CPS).[6] The figure shows an almost linear spreading out of the wage distributions for both men and women, substantial gains of women on men throughout the wage distribution, and declines in real earnings for males below the sixtieth percentile.

The timing of overall rising wage inequality (as measured by the ratio of the wages of the 90th to the 10th percentile worker) for men and women is illustrated in Figure 2. Rising wage inequality (driven initially by increases in within group inequality) began in the 1970s for men. The period from 1980 to 1985 of a deep recession and large decline in manufacturing employment is the period of most rapid growth of wage inequality. The rate of growth of wage inequality appears to have slowed down in the 1990s. Figure 3 combines men and women and presents the evolution of the real hourly wage of the 90th, 50th and 10th percentile workers from 1973 to 1998. The figure highlights the widening of the wage structure in the 1980s as well as some narrowing combined with rapid real wage growth since 1996.

It is sometimes argued that the large increases in U.S. wage and family income inequality over the last two decades have only small consequences for economic welfare because of the large amount of economic mobility in the United States. Although year-to-year earnings mobility is substantial, the evidence from multiple data sources shows no increase in the rate of earnings mobility in the United

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[6] Nominal wages are converted into constant dollars using the chain-weighted personal consumption expenditures deflator of the national income accounts. Many experts believe this deflator may fail to adequately capture consumer gains from new goods and quality improvement and thereby overstate the rate of increase of the cost of living (Boskin *et al*. 1998). Such adjustments would increase the estimates of real wage growth for all workers (by possibly 0.5 to 1 percent a year) but would not change conclusions about the growth of wage inequality or educational wage differentials.

States over recent decades (Katz and Autor 1999). This means that increases in cross-sectional wage inequality also translate into large increases in permanent (or lifetime) inequality.

A well-known analogy can help illuminate the nature of the increase in U.S. wage inequality (Condon and Sawhill 1992; Gottschalk and Danziger 1998). Wage inequality at a point in time is analogous to the situation of a group of people living in an apartment building with units that vary widely in quality. Each individual is assumed to have a one-year lease on a unit, and, therefore, the apartment dwellers have unequal accommodations in any given year. Earnings mobility is akin to movement between different apartment units. A substantial fraction of individuals switch apartment units both up and down the quality spectrum each year. But one should not overstate the degree of earnings mobility: those in the top quintile tend to stay in nice apartments and those in the bottom quintile only rarely make it into the upper units. The rise in wage inequality of the last two decades implies increased disparities in the quality of the different apartment units: the penthouse has become more luxurious with a better view and upgraded furniture, the middle units are largely unchanged, and the lower units have deteriorated markedly. Since the rate of earnings mobility has not increased and the disparities in apartments have increased, inequality measured over multiple years will increase.[7] A rise in disparities of apartments with constant mobility means an increase in the welfare consequences of the rank of the apartment unit to which one gets allocated.

Four primary (and partially complementary) explanations have been offered for the striking increase in wage inequality and returns to skill in the 1980s and early 1990s. The first attributes the primary role to increases in the rate of growth of the relative demand for highly educated and Amore-skilled@ workers arising from skill-biased technological changes driven by the diffusion of computer-

[7] Mobility can offset increases in cross-sectional inequality only if the rate of mobility also increases.

based technologies (Bound and Johnson, 1992; Berman, Bound, and Machin 1998). The second focuses on the role of globalization pressures (particularly increased trade with less-developed countries and greater foreign outsourcing) in reducing production employment and shrinking the relative demand for the less educated and leading to the loss of wage premia (labor rents) to some blue collar worker (Borjas and Ramey 1995; Wood 1994; Feenstra and Hanson 1999). The third emphasizes a slowdown in the rate of growth of the relative supply of skills because of the decline in the size of entering labor market cohorts in the 1980s and an increased rate of unskilled immigration (Katz and Murphy 1992; Murphy, Riddell, and Romer, 1998; Borjas, Freeman, and Katz 1997). The fourth explanation emphasizes changes in labor market institutions including the decline in unionization and the value of the minimum wage (DiNardo, Fortin, and Lemieux 1996; Lee 1999)

Sizeable and somewhat accelerated demand shifts favoring more-skilled workers, a reduction in the rate of growth of the relative supply of more-educated workers, and institutional changes all appear to have contributed to the large increase in U.S. wage inequality and educational wage differentials over the past two decades (Katz and Autor, 1999). Trade and outsourcing factors do not appear to be sufficiently large to be the major culprit (Borjas, Freeman, and Katz 1997; Berman, Bound, and Griliches 1994). The slowdown in the growth of wage inequality in the 1990s also is not consistent with a major role for trade with less-developed countries and outsourcing since these factors have grown much more rapidly in the 1990s than in the 1980s.

II. The Relative Supply of and Demand for Skills, 1940-98

Our understanding of the extent to which the large growth in U.S. wage inequality and educational wage differentials since the 1970s is driven by a technology-based acceleration of relative demand shifts favoring more-skilled workers requires can be enhanced by examining the evolution of the wage structure and the demand for and supply of skills over a longer time period. Although it is not possible to measure changes in the price and quantity of all skills (many of which are unobservable in available data sets), one can put together reasonably consistent data on the relative quantities and wages of workers by education from 1940 to 1998.

Table 1 displays the evolution of the educational composition of aggregate U.S. labor input (for those aged 18 to 65 years) measured in full-time equivalents (total hours worked) and of the college/high school wage ratio from 1940 to 1998.[8] The educational attainment of the work force increased rapidly over this fifty-eight year period with a more than four-fold increase in the share of hours worked by those with at least some college. Despite the large increase in the relative supply of the more educated, the college/high school wage differential has grown markedly since 1950 suggesting sharp secular growth in the relative demand for the more educated that started well before the rise in wage inequality of the 1980s.

Figure 4 illustrates the evolution of the college wage premium from 1940 to 1998. A sharp compression of educational wage differentials in the 1940s has been followed by expansions in each subsequent decade except the 1970s. Figure 5 displays the evolution of overall wage inequality (as measured by the 90-10 wage ratio) for men and women separately from 1940 to 1998. These series also indicate a large wage compression in the 1940s followed by widening inequality since

[8] The increases in the educational attainment of the U.S. work force since 1940 may overstate increases in the relative supply of more-skilled workers to the extent that the "unobserved" quality of more-educated workers declines with some re-labeling of less-skilled workers into higher education categories. Juhn, Kim, and Vella (1996) examine this issue using Census data from 1940 to 1990 and find that conclusions concerning changes in relative supply and implied relative demand shifts are not much affected by adjustments for such re-labeling.

1950,especially in the 1980s. Overall wage inequality and educational wage differentials have tended to move together with the exception of the 1970s. The college/high school wage gap and overall wage inequality are higher in 1998 than at anytime since 1940. But the earlier period from 1914 to 1939 was one of substantial declines in educational and occupational wage differentials so that wage disparities by education and occupation group are still below those in the early part of the century (Goldin and Katz 1999).

Table 2 presents estimates of changes in the college wage premium and in the relative supply of and demand for college equivalents over selected periods from 1940 to 1998.[9] The sharp difference in the behavior of the college relative wage in the 1970s and 1980s can be attributed both to slower relative supply growth and faster relative demand growth in the 1980s. A comparison of the period of large increase in the college wage premium from 1980-98 with the period of little change from 1960-80 suggests a deceleration in relative supply growth is more important than an acceleration in relative demand growth in explaining the recent expansion of educational wage differentials. A marked increase in the rate of growth of relative demand is apparent in the 1980s followed by a substantial decrease in the 1990s.

Table 2 implies strong secular relative demand growth for college workers since 1950 is necessary to reconcile the large increases in the college wage premium in the face of large relative

[9] The basic approach, following Katz and Murphy (1992) and Autor, Katz, and Krueger (1998) is to examine the relative wage of two "pure" skill groups (college graduates and high school graduates) and to relate this relative wage to changes in the relative quantities and demands for equivalents of these pure skill classes. College equivalents are given by college graduates plus half of those with some college; high school equivalents are half of those with some college plus workers with twelve or fewer years of schooling. Demand shifts for college equivalents are calculated under the assumption that the aggregate elasticity of substitution between college and high school equivalents is 1.4, approximately in the middle of the range of recent estimates (Katz and Autor 1999).

skill supply increases. The 1970s were an exceptional decade of rapid relative supply growth with the labor market entry of the baby-boom generation and increased college enrollments associated with the Vietnam War. The 1980s were the decade of most rapid relative demand growth, possibly suggesting an impact of the spread of personal computers and microprocessor-based technologies. The slowdown in demand growth in the 1990s indicates the period of the explosion of Internet commerce and communication has not been one of particularly rapid shifts in demand for college-educated workers.

Table 2 also indicates that the average rate of growth of relative demand for college workers was more rapid during the past twenty-eight years (1970-98) than during the previous thirty years (1940-70). This pattern is suggestive of an increased rate of skill-biased technological progress starting in the early 1970s as has been hypothesized by Greenwood and Yorukoglu (1997). But the evidence for a discrete trend break in overall demand growth is not very strong. And this conclusion is dependent on including the 1940s, a decade of strong institutional intervention in the labor market, in the earlier period.

What explains the strong trend growth in the relative demand for skills over the past fifty years and decadal fluctuations in the growth rate? A common approach is to conceptualize relative demand shifts as coming from two types of changes: those that occur within industries (i.e., shifts that change the relative factor intensities within industries at fixed relative wages) and those that occur between industries (i.e., shifts that change the allocation of total labor between industries at fixed relative wages). Sources of within-industry shifts include pure skill-biased technological change, changes in the relative prices (or supplies) of non-labor inputs (e.g., computer services or new capital equipment), and changes in outsourcing activity. Between-industry shifts in relative labor demand may be generated by sectoral differences in productivity growth and by shifts in product demand across industries arising either from domestic sources or from shifts in net international trade which change the domestic share of output in an industry at fixed wages. Shifts in employment between industries will have a larger effect on relative skill demands the greater are differences in skill intensities across industries.

This conceptualization has led to the use of decompositions of aggregate changes in the utilization of more-skilled labor into between-industry and within-industry components as a guide to the importance of product demand shifts as opposed to skill-biased technological change (or outsourcing) as sources of relative demand changes (Berman, Bound, and Griliches 1994; Katz and Murphy 1992). This research shows that throughout the twentieth century the industrial and occupational distribution of employment has shifted in favor of more-educated workers (Autor, Katz, and Krueger 1998; Goldin and Katz 1995; Juhn 1999). But measured between industry shifts appear to explain no more than twenty to forty percent of the secular growth in the relative demand for more-skilled workers. Substantial within-industry demand shifts must also have been a major factor. The pervasiveness of occupational and educational upgrading (even in industries outside of manufacturing with little foreign outsourcing) is quite suggestive of significant skill-biased technological change.

Autor, Katz, and Krueger (1998), using three-digit Census industries, find that the rate of within-industry relative demand growth for college workers increased from the 1960s to the 1970s and remained at a higher level in the 1980s through 1996. The large jump in within-industry skill upgrading occurred first in service industries in the 1970s and later in manufacturing industries in the 1980s. This timing pattern appears consistent with an earlier impact of computerization through organizational applications of computers on many service industries in the 1960s and 1970s and the somewhat later large-scale impact of microprocessor technologies on manufacturing production processes. These findings motivate a more detailed and direct look at the evidence on the impact on labor demand of skill-biased technological change and the spread of computers.

III. Technological Change, Computerization, and the Demand for Skills

The deteriorating labor market outcomes of less-educated workers in most OECD economies from the 1970s to the mid-1990s despite their increasing relative scarcity strongly implies a strong decline in the relative demand for less-skilled workers. Skill-biased technological change and increased exposure to international competition from less developed countries have been offered as the leading explanations for this demand shift.

Much indirect evidence suggests a dominant role for skill-biased technological change (associated with changes in production techniques, organizational changes, and reductions in the relative prices of computer services and new capital equipment) in the declining relative demand for the less skilled. First, the magnitude of employment shifts to skill-intensive industries as measured by between-industry demand shift indices is too small to be consistent with explanations giving a leading role to product demand shifts, such as induced by greater trade with developing countries. Estimates of between-industry demand shifts also show little evidence of acceleration in recent decades. Second, despite increases in the relative wages of more-skilled workers, the composition of U.S. employment continues to shift rapidly towards more-educated workers and higher-skill occupations within industries and even within establishments (Autor, Katz, and Krueger 1998; Dunne, Haltiwanger, and Troske 1996). Third, within-industry skill upgrading despite rising or stable skill premia is apparent in found in almost all industries in many other developed economies in the 1980s. The cross-industry pattern of the rate of skill upgrading in manufacturing industries appears to be quite similar among advanced nations (Berman, Bound, and Machin 1998). These findings suggest an important role for *pervasive* skill-biased technological change concentrated in similar industries in all OECD countries as a major source of changes in relative skill demands.

There also exist strong positive correlations between industry-level indicators of technological change (computer investments, the growth of employee computer use, research and development (R&D) expenditures, utilization of scientists and engineers, changes in capital intensity measures) and the within-industry growth in the relative employment and labor cost share of more-skilled workers (Autor, Katz, and Krueger 1998; Berman, Bound, and Griliches 1994; Machin and Van Reenen 1998, Wolff 1996). The causal interpretation of contemporaneous correlations of technology indicators such as R&D intensity and computer use with skill upgrading is unclear since R&D activities directly use highly-educated workers and since other sources of changes in the use of skilled workers could drive variation across industries in purchases of computers. But Autor, Katz, and Krueger (1998), Machin and Van Reenen (1998), and Wolff (1996) find that lagged computer investments and R&D expenditures predict subsequent increases in the pace of skill upgrading. This pattern is consistent with a recent survey of U.S. human resource managers indicating that large investments in information technology lead to changes in organizational practices that decentralize decision-making, increase worker autonomy, and increase the need for highly-educated workers (Bresnahan, Brynjolfsson, and Hitt 1999).

Plant-level studies of U.S. manufacturing by Bernard and Jensen (1997) and Doms, Dunne, and Troske (1997) similarly find strong positive relationships between within-plant skill upgrading and both R&D intensity and computer investments. But Doms, Dunne, and Troske (1997) find little relationship between a plant-level indicator of the number of new factory automation technologies being used and subsequent within-plant skill upgrading. In contrast, case studies by the Bureau of Labor Statistics indicate large production labor saving production innovations were adopted in the 1970s and 1980s in the electrical machinery, machinery, and printing and publishing sectors -- three industries that are among the leaders in the rate of skill upgrading in most developed countries (Berman, Bound, and Machin 1998; Mark 1987).

The diffusion of computers and related technologies represents a possibly significant measurable source of recent changes in the relative demand for skills. The share of U.S. workers using computers on the job, an extremely crude measure of the diffusion of computer-based technologies, increased from 25 percent in 1984 to 51 percent in 1997 (Friedberg 1999).[10] Although most workers use computers largely for common applications (word processing, spreadsheets, and databases), Friedberg (1999) finds that approximately 47 percent of those with work-place computers used them for electronic mail or other communication tasks in 1997. Table 3 shows that the growth in work-place computer use has not been uniform across demographic or skill groups. Women, college educated workers, whites, and white collar workers are more likely to use computers and have experienced greater wage growth since 1979 than men, non-college workers, blacks, and blue collar workers respectively.

Krueger (1993) and Autor, Katz, and Krueger (1997) document a substantial wage premium associated with computer use (conditional on large set of controls for observed worker

[10] The rapid spread of computers in the work place appears to have occurred at a similar pace in other OECD countries (Card, Kramarz, and Lemieux 1996).

characteristics) that increased from 18 percent in 1984 to 20 percent in 1993. The extent to which this computer wage premium represents a measure of the true returns to computer skills (the treatment effect of computer use) or largely reflects omitted characteristics of workers and their employers is a subject of much controversy (see, for example, DiNardo and Pischke (1997)). But the causal interpretation of such regressions does not directly address the issue of whether the spread of computer technologies has changed organizational practices and altered relative skill demands.

Computer technology may affect relative labor demand in several ways.[11] Computer business systems often involve the routinization of many white-collar tasks. Simpler and more repetitive tasks have proved more amenable to computerization than more complex and idiosyncratic tasks. Microprocessor-based technologies have similarly facilitated the automation of many production processes in recent years. The direct substitution of computers for human judgment and labor is likely to have been more important in clerical and production jobs than in managerial and professional jobs. Computer-based technologies may also increase the returns to creative use of greater available information to more closely tailor products and services to customers’ specific needs and to develop new products. Computers, the Internet, and electronic commerce also raise the returns to marketing and problem solving skills to better match customers’ idiosyncratic preferences to existing products and service. Bresnahan (1999) posits such an organizational complementarity between computers and workers who possess both greater cognitive skills and greater “people” or “soft” skills.

The direct substitution and organizational complementarity channels both predict that an increase in the relative demand for highly educated workers and occupations stressing “soft” skills

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[11] See Bresnahan (1999) for a descriptive theory of and illuminating historical evidence on how computerization influences labor demand and organizational practices.

should be associated with computerization. These predictions are consistent with the findings of Autor, Katz, and Krueger (1998) that increased computer intensity is associated with increased employment shares of managers, professionals and other highly educated workers, and with decreased employment shares of clericals, production workers, and less educated workers. Bresnahan, Brynjolfsson and Hitt (1999) also find in firm-level data that greater use of information technology is associated with the employment of more-educated workers, greater investments in training, broader job responsibilities for line workers, and more decentralized decision-making.

Several conceptual issues concerning the nature of how technological change affects the labor market merit further consideration to sort out the long-run implications of computerization and the rise of the digital economy. One possibility is that skilled workers are more flexible and facilitate the adoption of new technologies so that all technological changes increase the relative demand for more-skilled labor over some transitional period (Bartel and Lichtenberg 1987; Greenwood and Yorukoglu 1997). As technologies diffuse and become mature and more routinized the comparative advantage of the highly skilled declines. In this case the demand for skilled labor depends on the rate of innovation. Periods of large increases in the skill premium correspond to technological revolutions.[12]

Under this interpretation, the apparent slowdown in growth of the relative demand for skill in the 1990s could reflect such a maturing of the computer revolution. The naive measure of employee computer use in Table 3 does show a slowdown in the rate of diffusion from the 1984-93 period to the 1993-97 period. This interpretation also implies that the expansion of the Internet and electronic commerce may have much smaller labor market impact than the spread of large-scale computing operations in the 1970s and of personal computers in the 1980s and early 1990s. Of course, we may

[12] See Galor and Moav (2000) for an insightful model of the rate of technological innovation, changes in

only be observing the tip of the iceberg and there may be major organizational changes associated with electronic communications that could lead to large transitory impacts on the relative demand for skills. Furthermore the improvements in the relative and real labor market position of less-skilled workers over the past few years may largely reflect transitory factors associated with extremely strong macroeconomic conditions (Katz and Krueger 1999).

An alternative (but potentially complementary) hypothesis is that distinctive technological innovations may have different skill biases. Some of the main technological changes of the twentieth century associated with electrification and computerization may have been skill-biased, but other innovations need not be. Mechanization in the nineteenth century associated with the movement from artisanal production (intensive in skilled craft workers) to factory production (intensive in unskilled labor) appears to have been largely deskilling even though more flexible workers were likely to have been necessary to assist in the introduction of factory methods (Goldin and Katz 1998). Under this scenario the inherent skill-biased nature of twentieth century innovations rather than an accelerating rate of innovation is the source of secular within-industry growth in the relative demand for skill.[13]

IV. Conclusions and Research Directions

Strong secular growth in the relative demand for more-educated and more-skilled workers has been apparent throughout the twentieth century in the United States. Skill-biased technological changes ranging from the electrification to computerization have been major factors in this steady growth in the relative demand for skill. The overall rate of relative demand growth for college-

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educational attainment, and the evolution of wage inequality.

[13] See Acemoglu (1998) for an insightful model of how increases in the proportion of more-educated workers (as have occurred throughout the twentieth century) can induce the development of skill-complementary technologies.

educated workers appears to have been particularly rapid in the 1980s and then slowed in the 1990s. The pace of within-industry skill upgrading increased from the 1960s to the 1970s throughout the economy, further increased in manufacturing in the 1980s, and has remained high in the 1990s. Indicators of employee computer usage, computer capital intensity, and the rate of investment in information technologies are higher in industries with more rapid rates of skill upgrading in each of the last several decades. Thus skill-biased technological and organizational changes that accompanied the computer revolution appear to have contributed to faster growth in relative skill demand within industries starting in the 1970s.

Although the strong observed conditional correlations of computer measures and the growth in the relative utilization of highly educated workers may not just reflect causal relationships, it is clear that whatever is driving the rapid rate of relative demand growth for more-skilled workers over the past few decades is concentrated in the most computer-intensive sectors of the U.S. economy. But these patterns do leave substantial room for fluctuations in the rate of growth of the supply of college equivalents, globalization forces, and changes in labor market institutions to also have contributed to recent movements in U.S. wage inequality and educational wage differentials.

Our understanding of how new computer-based technologies are affecting the labor market has been hampered by the lack of large representative data sets that provide good measures of work-place technology, worker technology use, firm organizational practices, and worker characteristics. Research on representative national data sets has been forced to use crude measures of employee computer usage from the occasional supplements to the CPS or has had to link CPS data on worker characteristics to noisy measures of industry-level information technology investments and capital stocks. Matched employer-employee data sets with detailed information on technologies, worker attributes, and personnel practices would greatly enhance our ability to sort out how new technologies are affecting skill demands and the organization of work. The linked data sets for manufacturing workers and plants from the 1990 Census of Population, the Longitudinal Research Database, and the 1988 and 1993 Survey of Manufacturing Technologies used by Doms, Dunne, and Troske (1997) provide a fine example of data collection efforts moving in this direction. But we need such data sets also for non-manufacturing industries.

The other major methodological issue involves moving from correlations between technology indicators and skill upgrading to learning more about causal relations from finding and examining "exogenous" changes in firms access to or costs of purchasing new technologies. Studies of the effects on skill demands of the differential effects of tax changes on firms' investment incentives might be a useful start. Case studies of how sharp changes in firm technologies and computer use affect organizational practices and relative skill demands also are proving fruitful (e.g., Levy and Murnane 1996; Ichniowski, Shaw, and Prennushi 1997; Bresnahan, Brynjolfsson, and Hitt 1999).

Several issues concerning how the digital economy is affecting the labor market merit further study. A first research issue concerns how the growth of the Internet is affecting the geographic distribution of production and employment opportunities among large cities, smaller cities, suburban areas, and rural areas (Gaspar and Glaeser 1998; Kolko, 1999). A second topic involves the sources of employee training in a rapidly changing digital economy. Autor (1999) has documented an increasing role of temporary help firms in providing limited computer skills training.

A final issue for further scrutiny is how the Internet job search and computer-oriented labor market intermediaries (the rapidly growing temporary help industry) are affecting labor market matching and the ability of the economy to operate with a low unemployment rate. There has been a striking decline in short-term unemployment in the United States in the 1990s with a lower proportion of the labor force flowing through unemployment by 1997 than in anytime in the past forty years (Katz and Krueger 1999). Suggestive evidence indicates improvements in labor market matching and greater labor market competition from the growth of labor market intermediaries may be playing a role in reducing labor market bottlenecks and potentially lowering the natural rate of unemployment. Increased software compatibility across work sites that allows new employees to quickly integrate into many computer-oriented jobs may be having a similar effect.

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Table 1
U.S. Educational Composition of Employment and the College/High School Wage Premium, 1940-1998

	Full-Time Equivalent Employment Shares by Education Level (in percent)				
	High School Dropouts	**High School Graduates**	**Some College**	**College Graduates**	**College/HS Wage Ratio**
1940 Census	67.9	19.2	6.5	6.4	1.65
1950 Census	58.6	24.4	9.2	7.8	1.38
1960 Census	49.5	27.7	12.2	10.6	1.49
1970 Census	35.9	34.7	15.6	13.8	1.59
1980 Census	20.7	36.1	22.8	20.4	1.48
1980 CPS	19.1	38.0	22.0	20.9	1.43
1990 CPS	12.7	36.2	25.1	26.1	1.66
1990 Census	11.4	33.0	30.2	25.4	1.73
Feb. 90 CPS	11.5	36.8	25.2	26.5	1.70
1998 CPS	9.4	33.3	28.3	29.1	1.75

Sources: Data for 1940 to 1990 are from Autor, Katz, and Krueger (1998, Table I). Data for 1998 are from the 1998 Merged Outgoing Rotation Groups of the CPS using the same methodology.

Notes: Full-time equivalent (FTE) employment shares are calculated for samples that include all individuals ages 18-65 in paid employment during the survey reference week for each Census and CPS sample. FTE shares are defined as the share of total weekly hours supplied by each education group. The tabulations are based on the 1940 to 1990 Census Integrated Public Use Micro samples; the 1980, 1990, and 1998 CPS Merged Outgoing Rotation Group samples; and the February 1990 CPS. The 1990 Census, February 1990 CPS, and 1998 CPS samples use the new Census education variable. The Data Appendix to Autor, Katz, and Krueger (1998) discusses how the old and new education coding schemes are made comparable.

The college/high school wage ratio for each year is the (exponentiated) weighted average of the estimated college (exactly 16 years of schooling or bachelor's degree) and post-college (17+ years of schooling or a post-baccalaureate degree) log wage premium relative to high school workers (those with exactly 12 years of schooling or a high school diploma) for that year, where the weights are the employment shares of college and post-college workers in 1980. The details of the specifications and estimation approach are given in Autor, Katz, and Krueger (1998).

TABLE 2: Growth of College/High School Relative Wage, Supply, and Demand, Selected Periods, 1940-98 (Annualized Percent Changes)

	Relative Wage	Relative Supply	Relative Demand
1940-50	-1.86	2.35	-0.25
1950-60	0.83	2.91	4.08
1960-70	0.69	2.55	3.52
1970-80	-0.74	4.99	3.95
1980-90	1.51	2.53	4.65
1990-98	0.36	2.25	2.76
1940-70	-0.11	2.61	2.45
1970-98	0.38	3.33	3.86
1940-60	-0.51	2.63	1.92
1960-80	-0.02	3.77	3.74
1980-98	1.00	2.41	3.81

SOURCE: Autor, Katz, and Krueger (1998, Table II), updated to 1998.

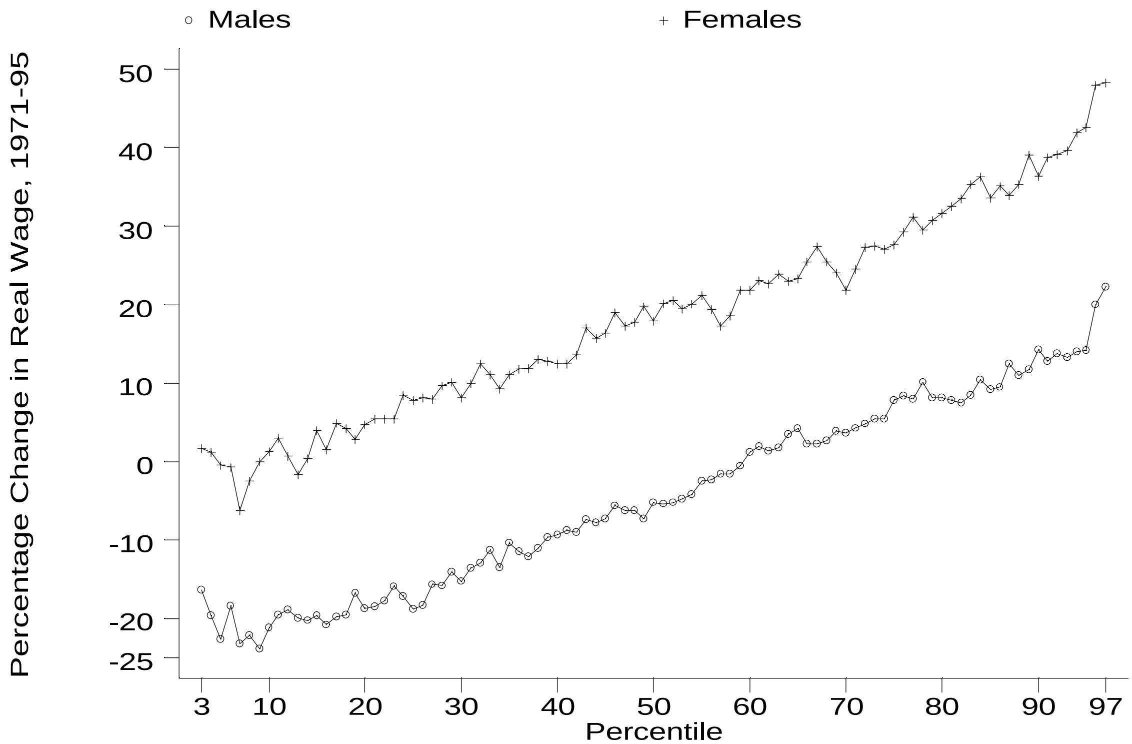
Notes: The relative wage measure is the log of the college/high school wage ratio from Table 1. The relative supply and demand measures are for college equivalents (college graduates plus half of those with some college) and high school equivalents (those with 12 or fewer years of schooling and half of those with some college). The implied relative demand changes assume an aggregate elasticity of substitution between college equivalents and high school equivalents of 1.4. The relative supply measure adjusts for changes in the age-sex composition of the pools of college and high school equivalents; see Autor, Katz, and Krueger (1998) for details.

Table 3
Percent of Workers in Various Categories Who Directly Use a Computer at Work, 1984 to 1997

	1984	1989	1993	1997
All workers	24.4	37.3	46.6	50.6
Education				
< High School	4.9	7.7	9.5	11.7
High School	18.5	28.5	34.1	36.4
Some College	31.2	44.8	53.1	56.2
College +	41.2	58.6	70.2	75.9
Race and Sex				
White, male	21.6	32.9	42.3	46.3
White, female	30.5	44.9	54.8	58.9
Black, male	12.6	21.7	29.7	32.3
Black, female	22.6	33.8	43.3	47.8
Occupation				
Professional, Technical	38.1	54.4	65.7	73.1
Managers, Administrators	42.5	61.8	73.7	78.7
Sales	23.9	35.5	49.8	55.8
Clerical	47.4	66.8	77.4	78.6
Craft	10.1	15.2	23.5	25.3
Operatives	5.8	9.6	15.7	18.6
Laborers	3.2	6.6	11.7	12.8
Service	6.0	9.8	15.1	16.8

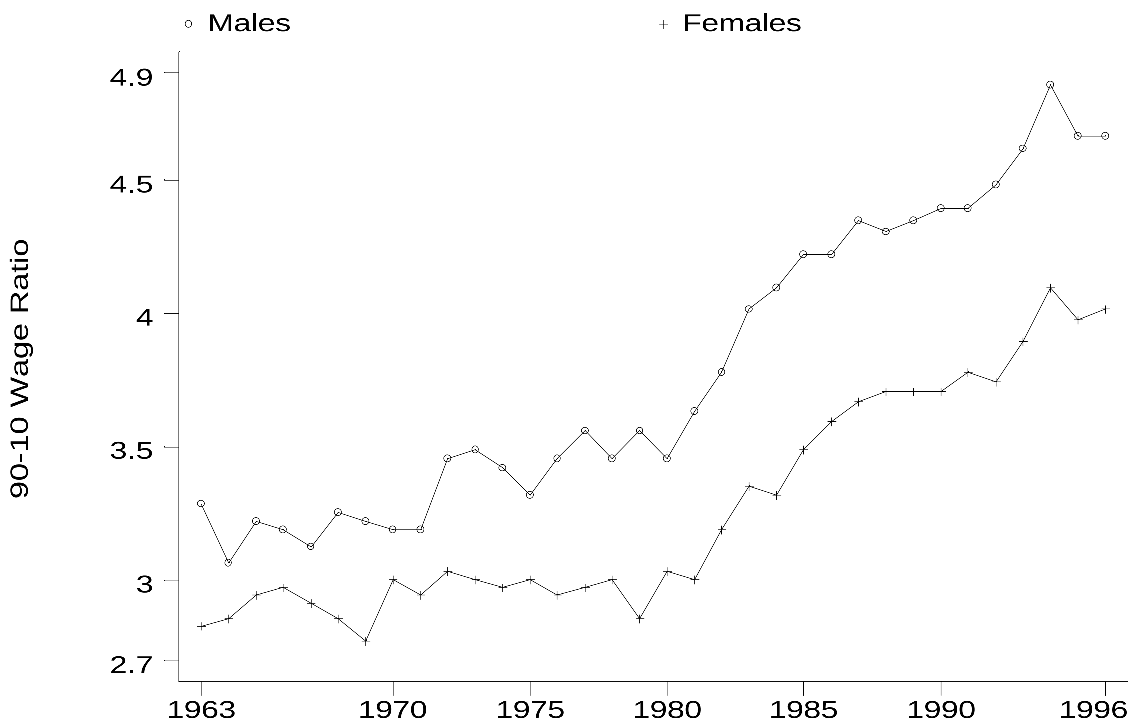
Source: Friedberg (1999, Tables 2 and 4).
Notes: Tabulations of computer use at work from the October 1984, 1989, 1993, and 1997 CPS samples for individuals aged 18-64 at work or with a job in the survey reference week. A computer is defined as a PC or desktop terminal with a keyboard and monitor.

Figure 1: Percentage Change in Real Weekly Wage by Percentile, 1971-95



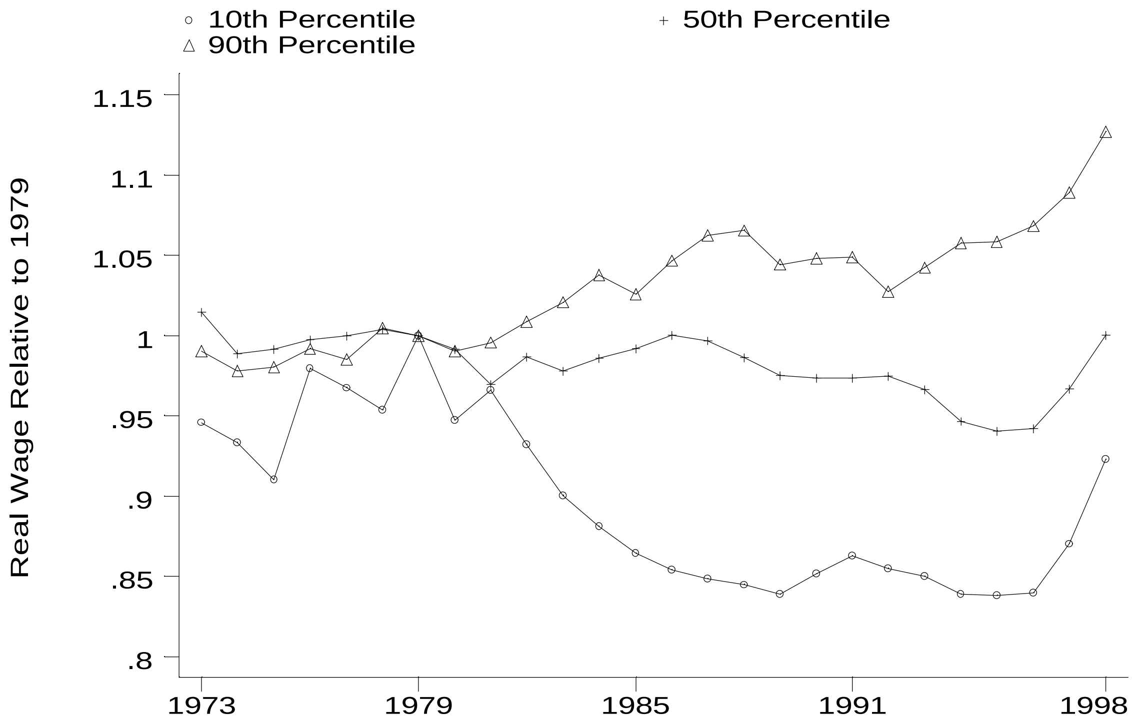
Source: Full-time, full-year wage and salary workers from the March Current Population Surveys, 1972 to 1996. Wages are deflated by the personal consumption expenditures deflator of the national income accounts. See Katz and Autor (1999) for detailed information on the sample selection and data processing procedures.

Figure 2: Overall U.S. Wage Inequality, 1963-96



Source: Full-time, full-year wage and salary workers from the March Current Population Surveys, 1964 to 1997. The 90-10 wage ratio is the ratio of the weekly earnings of the worker in the 90th percentile of the earnings distribution to the weekly earnings of the worker in the 10th percentile.

Figure 3: Indexed Real Hourly Wage by Percentile, 1973-98 (1979=1)



Source: Data on hourly wages by decile for all workers are from the May CPS samples for 1973-78 and from the CPS Merged Outgoing Rotation Group samples for 1979-98. Jared Bernstein of the Economic Policy Institute provided the underlying data. Nominal wages are deflated by the personal consumption expenditures deflator from the national income accounts. The real wage relative to 1979 is the ratio of the real wage in that year to the real wage in 1979 at the same percentile in the wage distribution.

Figure 4: The College/High School Wage Ratio, 1940-98

Source: Table 1.

Figure 5: Overall U.S. Wage Inequality, 1940-98

Source: Estimates are for the weekly wages of full-time, full-year workers not employed in agriculture and earning at least half of the federal minimum wage. The estimates for 1940 to 1990 are from Katz and Autor (1999, Table 8), and the estimated changes from 1990 to 1998 are from Bernstein and Mishel (1999). The 90-10 wage ratio is the ratio of the earnings of the worker in the 90th percentile of the earnings distribution to the earnings of the worker in the 10th percentile.