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Technical Change, Inequality, and the Labor Market

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1. *Introduction*

1.1 *Motivation*

What are the implications of technical change for the labor market? How does new technology affect the distribution of wages and income? Is technology responsible for the changes in the wage structure observed in many advanced economies since the 1970s?

The recent consensus is that technical change favors more skilled workers, replaces tasks previously performed by the unskilled, and exacerbates inequality. This view is shaped largely by the experience of the past several decades, which witnessed both major changes in technology, including the rapid spread of computers in workplaces and in our lives, and a sharp increase in wage inequality. In the United States, for example, the college premium—the wages of college graduates relative to the wages of high-school graduates—increased by over 25 percent between 1979 and 1995. Overall earnings inequality also increased sharply. In 1971, a worker at the 90th percentile of the wage distribution earned 266 percent more than a worker at the 10th percentile. By 1995 this number had risen to 366 percent (author's calculations from March CPS data). Many commentators see a direct causal relationship between technological changes and these radical shifts in the distribution of wages taking place in the U.S. economy. The title of Alan Krueger's (1993) influential paper on computers and inequality summarizes this view: "How Computers Have Changed the Wage Structure." Jeremy Greenwood and Mehmet Yorukoglu (1997, p. 87) similarly give a succinct statement:

> Setting up, and operating, new technologies often involves acquiring and processing information. Skill facilitates this adoption process. Therefore, times of rapid technological advancement should be associated with a rise in the return to skill.

They further argue that we are now in the midst of a "Third Industrial Revolution," fueled by advances in information technology, and that this revolution is responsible for the increase in inequality (as does Francesco Caselli 1999, in a paper entitled "Technological Revolutions").

The view that technological developments favor skilled workers also receives support from accounts of earlier

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episodes. For example, there were already signs of significant *technology-skill complementarity* in the 1910s. Claudia Goldin and Lawrence Katz (1998) argue that the spread of batch and continuous-process methods of production increased the demand for skills. They add, ". . . the switch to electricity from steam and water-power energy sources was reinforcing because it reduced the demand for unskilled manual workers in many hauling, conveying, and assembly tasks" (p. 695). Over this period, capital-intensive industries increased the demand for skills considerably (see Goldin and Katz 1998, table 3), and the scope of these industries expanded with the sharp fall in the price of electricity (see, for example, Arthur Woolf 1984, p. 178). The rapid increase in the importance of white-collar and clerical occupations gave another boost to the demand for skills. Generalizing from the experience of the 1920s, Harry Jerome (1934, p. 402) argued that ". . . in the future . . . there is considerable reason to believe that the effect of further [mechanization] will be to raise the average skill required."

The early twentieth-century evidence was so powerful that Zvi Griliches (1969) suggested capital and skills are intrinsically complementary. Richard Nelson and Edmund Phelps (1967), Finis Welch (1970), Theodore Schultz (1975), and Jan Tinbergen (1975) also argued that technological developments increase the demand for skills. Events since then support this notion. Personal computers, computer-assisted production techniques, and robotics appear to complement skilled workers, replacing many labor-intensive tasks. In this light, it is perhaps natural to view the increase in inequality over the past several decades as a direct consequence of technical change.

Although the consensus is now broad, the idea that technological advances favor more skilled workers is a twentieth-century phenomenon. In nineteenth-century Britain, skilled artisans destroyed weaving, spinning, and threshing machines during the Luddite and Captain Swing riots, in the belief that the new machines would make their skills redundant. They were right: the artisan shop was replaced by the factory and later by interchangeable parts and the assembly line (e.g., John James and Jonathan Skinner 1985; Goldin and Katz 1998). Products previously manufactured by skilled artisans started to be produced in factories by workers with relatively few skills, and many previously complex tasks were simplified, reducing the demand for skilled workers.[2] Joel Mokyr (1990, p. 137) describes this process vividly:

> First in firearms, then in clocks, pumps, locks, mechanical reapers, typewriters, sewing machines, and eventually in engines and bicycles, interchangeable parts technology proved superior and replaced the skilled artisans working with chisel and file.

[2] In the absence of detailed econometric evidence, it is difficult to generalize from the historical examples and conclude that technical change was definitely skill-replacing during the nineteenth century. Still, the only econometric evidence that I am aware of supports this view. Using the 1850 Census of Manufacturers, James and Skinner (1985) find that there was more rapid substitution of capital for skilled workers than unskilled workers. It can also be argued that technical change always increases the demand for "skills," and the artisans who were hurt as a result of new technology were not "skilled" since they lacked the flexibility to adapt to the required changes. This argument is not totally convincing, since the artisans earned considerably more than other laborers (for example, James and Skinner 1985 report over 60 percent wage differentials for building and printing workers relative to laborers in the 1850s). So the artisans possessed skills that were being rewarded by the market, and the standardization of the production process destroyed these rewards. On the other hand, it has to be noted that many of the skill-replacing technologies of the nineteenth century may have also increased the demand for engineers and managers (see, e.g., Goldin and Katz 1998).

Interchangeable parts were in fact very much designed to be skill-replacing (unskill-biased). Eli Whitney, a pioneer of interchangeable parts, described the objective of this technology as:

> . . . to substitute correct and effective operations of machinery for the skill of the artist which is acquired only by long practice and experience; a species of skill which is not possessed in this country to any considerable extent. . . . (quoted in H. J. Habakkuk 1962, p. 22)

The experience of the nineteenth and early twentieth centuries led Harry Braverman (1974) and Stephen Marglin (1974) to argue that technical change was "deskilling"—a major purpose of technical change was to expand the division of labor and simplify tasks previously performed by artisans by breaking them into smaller, less skill-requiring pieces. Braverman (1974, p. 113), for example, suggested that the first principle of management and production techniques of the period was "dissociation of the labor process from skills of the workers. The labor process is to be rendered independent of craft, tradition, and the workers' knowledge."

A longer view therefore suggests that technological advances may not have always increased the demand for skills. In fact, most early nineteenth-century innovations appear to have replaced skilled workers and expanded tasks performed by the unskilled. But then, why have technological advances been skill-biased in the twentieth century? And, are technological changes *the major cause* of the recent increase in inequality?

This essay attempts to answer these questions. It has two main theses:

- The behavior of wages and returns to schooling indicates that technical change has been skill-biased during the past sixty years and probably for most of the twentieth century. Furthermore, an acceleration in skill bias during the past few decades appears to be the main cause of the increase in inequality.
- We can understand the behavior of technical change by recognizing that the development and use of technology is, at least in part, a response to profit incentives.[3] When developing skill-biased techniques is more profitable, new technology will tend to be skill-biased. I suggest that the early nineteenth century was characterized by skill-replacing developments because the increased supply of unskilled workers in the English cities (resulting from migration from rural areas and from Ireland) made the introduction of these technologies profitable. In contrast, the twentieth century has been characterized by skill-biased technical change because the rapid increase in the supply of skilled workers has *induced* the development of skill-complementary technologies. The recent acceleration in skill-biased technical change is in turn likely to have been a response to the rapid increase in the supply of skills during the past several decades. However, I also argue that despite the acceleration in skill bias, we are most likely not in the midst of a "technological revolution"; what has changed is not necessarily the overall rate of progress, but the types of technologies that are being developed.

[3] Precedents of this approach include Jacob Schmookler (1966), who emphasized *demand pull* and the extent of the market as key determinants of innovations; the endogenous growth theory, e.g., Paul Romer (1990), Gene Grossman and Elhanan Helpman (1991), and Philippe Aghion and Peter Howitt (1992); the induced innovation theory, including Syed Ahmad (1965), Charles Kennedy (1964), Paul Samuelson (1970), Yujiro Hayami and Vernon Ruttan (1970), and Paul David (1975); and recent work including my own, Acemoglu (1998, 1999b, 2000), Acemoglu and Fabrizio Zilibotti (1999), and Michael Kiley (1999).

Finally, I conjecture that recent technological developments are likely to have affected the organization of the labor market—including the way firms are organized, labor market policies, and the form of labor market "institutions"—and may have had a large effect on the structure of wages through this channel.

In the process of developing this argument, this essay sets out a simple theoretical framework in which inequality and returns to skills are determined by supply and demand forces (technology).[4] Using this framework as a unifying device, I critically survey many of the theories that explain the recent increase in inequality by technological factors and discuss how various pieces of evidence can be interpreted within this framework.

1.2 *Summary of the Argument*

I begin with a roadmap of the argument. Since the effect of new technology on the distribution of wages in the recent past is central to the focus here, I organize this essay around a number of salient facts from the post-war U.S. economy.[5] Briefly, these facts are:

1. The past sixty years have seen a large increase in the supply of more educated workers, while returns to education have risen.
2. Returns to education fell during the 1970s, when there was a very sharp increase in the supply of educated workers. Returns to education then began a steep rise during the 1980s.
3. Overall wage inequality rose sharply beginning in the early 1970s. Increases in within-group (residual) inequality—i.e., increases in inequality among observationally equivalent workers—account for much of this rise.
4. Average wages have stagnated and wages of low-skill workers have fallen in real terms since 1970.

I argue that technical change over the past sixty years, or even over the past century, has been skill-biased. This conclusion follows from fact 1 above: in the absence of substantial skill bias in technology, the large increase in the supply of skilled workers would have depressed the skill premium. In 1970, Welch (1970, p. 36) reached the same conclusion, and argued:

> With the phenomenal rise in average education, why have rates of return failed to decline? . . .
>
> It is obvious that changes have occurred to prevent the decline in returns to acquiring education that would normally accompany a rise in average educational level. Presumably, these changes have resulted in growth in demand for . . . education . . . sufficient to absorb the increased supply with constant or rising returns.

The thirty years after Welch wrote these words witnessed a much more rapid increase in the supply of education and a sharp increase in the returns to more skilled workers, suggesting that skill-biased changes in technology continued throughout the postwar period.

And yet, if technical change has been skill-biased throughout the recent past, why did inequality increase during the past thirty years, but not before? There are at least two possible answers to this question. The first, which I call the *steady-demand hypothesis*, maintains that demand for skills increases at a constant pace, so changes in inequality must be explained by the pace of the increase in the supply of skills. According to this hypothesis, inequality (returns to skills)

[4] Precedents of the supply and demand approach include, among others, Gary Becker (1964), Finis Welch (1970), and Jan Tinbergen (1975).

[5] I limit the discussion of the major trends to the U.S. economy because of space constraints and also because there is notably more research to build upon.

was relatively stable before the 1970s, because the rate of skill accumulation in the U.S. economy was as rapid as the constant pace of skill-biased technical change (e.g., Katz and Kevin Murphy 1992; Murphy, Craig Riddell, and Paul Romer 1998; David Card and Thomas Lemieux 2000). The recent increase in inequality is then explained, not by a major technological change, but by a decline in the growth rate of the supply of skills. The second possible answer comes from the *acceleration hypothesis*, which maintains that there has been an acceleration in skill bias beginning in the 1970s or the 1980s. According to this hypothesis, there is a discontinuity in the growth rate of the demand for skills. The most popular version of this hypothesis claims that there has been a notable acceleration in the skill bias of technology, driven by advances in information technology, or perhaps a "Third Industrial Revolution."

So was there an acceleration in skill bias? This question is difficult to answer, as we lack direct measures of the degree of skill bias. To tackle this question, one therefore needs to look at a variety of evidence often pointing in different directions. I conclude below that skill-biased technical change is likely to have accelerated over the past several decades. This conclusion is based on the sharp increase in overall inequality starting in the 1970s and on the fact that returns to schooling rose over the past thirty years despite the unusually rapid increase in the supply of educated workers.

Why did the demand for skills accelerate over this period? And why has new technology favored more skilled workers throughout the twentieth century, but not during the nineteenth century? One approach would view technology as exogenous, stemming from advances in science or from the behavior of entrepreneurs driven by a variety of nonprofit motives. Demand for skills increased faster during the past thirty years, this approach would maintain, because of a *technological revolution* led by the microchip, personal computers, and the internet.[6] New technologies of the early nineteenth century were skill-replacing (unskill-biased) because the technological frontier then only enabled the invention of skill-replacing techniques.

Nevertheless, there are several problems with this approach. First, although a number of papers, including Greenwood and Yorukoglu (1997), Andres Hornstein and Krusell (1997), and Galor and Moav (2000), show that rapid technical change may lead to slower total factor productivity (TFP) growth, the slow rates of TFP and output growth of the past several decades are difficult to reconcile with a technological revolution during this time period. Second, demand for skills appears to have accelerated starting in the late 1970s, precisely when the supply of skills increased very rapidly. Exogenous technology theories do not explain the timing of this acceleration.[7]

[6] See, among others, Krueger (1993), Eli Berman, John Bound, and Griliches (1994), and David Autor, Katz, and Krueger (1998) for evidence that the rapid spread of computers has increased the demand for skills. See Per Krusell, Lee Ohanian, Victor Rios-Rull, and Giovanni Violante (2000), Oded Galor and Daniel Tsiddon (1997), Greenwood and Yorukoglu (1997), Aghion and Howitt (1998, ch. 9), Caselli (1999), Galor and Omer Moav (2000), Violante (2000), Yonna Rubinstein and Tsiddon (1999), Aghion, Howitt, and Violante (2000), and Eric Gould, Moav, and Bruce Weinberg (2000) for models in which rapid technical change increases the demand for skills and causes a rise in inequality.

[7] Naturally, supply and demand may have moved together because supply responded to demand. I argue below that the large increase in the supply of educated workers was not in anticipation of, or in response to, high returns, but driven by a variety of other factors. More generally, I often focus on the effect of the supply of skills on technology not because I view supply as exogenous,

An alternative theory maintains instead that new technologies are *endogenous* and respond to incentives. It was the large increase in the supply of skilled workers, this approach claims, that induced the acceleration in the demand for skills. When skill-biased techniques are more profitable, firms will have greater incentives to develop and adopt such techniques. A key determinant of the profitability of new technologies is their market size; machines that can be sold in greater numbers will be more profitable. Jacob Schmookler (1966), in his pioneering study, *Invention and Economic Growth*, placed great emphasis on market size. He argued that (p. 206) "invention is largely an economic activity which, like other economic activities, is pursued for gain; . . . expected gain varies with expected sales of goods embodying the invention." This reasoning implies that machines complementary to skilled workers will be more profitable to develop when there are more skilled workers to use them. New technologies have become more skill-biased throughout most of the twentieth century because the supply of skilled workers has grown steadily. This perspective also suggests that a faster increase in the supply of skills can lead to an acceleration in the demand for skills (Acemoglu 1998). So the timing of the increases in supply and demand is not a coincidence—instead, it reflects technology responding to the supply of skills. Furthermore, rapid skill-biased technical change is not necessarily associated with rapid overall technical progress. In fact, an acceleration in skill bias could cause a TFP slowdown because it creates an imbalance in the composition of R&D.

This approach also provides a possible explanation for the skill-replacing technical change of the early nineteenth century. The emergence of the most skill-replacing technologies of the past two hundred years, the factory system, coincided with a large change in relative supplies. This time, there was a large migration of unskilled workers from villages and Ireland to English cities (see, for example, Habakkuk 1962; Paul Bairoch 1988; or Jeffrey Williamson 1990). This increase in the "reserve army of unskilled workers," slightly paraphrasing Karl Marx, created profit opportunities for firms to exploit by introducing technologies that could be used with unskilled workers. In fact, contemporary historians considered the incentive to replace skilled artisans by unskilled laborers to be a major objective of technological improvements of the period. Ure, a historian in the first half of the nineteenth century, describes these incentives as follows:

> It is, in fact, the constant aim and tendency of every improvement in machinery to supersede human labor altogether, or to diminish its costs, by substituting the industry of women and children for that of men; of that of ordinary labourers, for trained artisans. (quoted in Habakkuk 1962, p. 154)

These incentives for skill-replacing technologies, I argue, were shaped by the large increase in the supply of unskilled workers. So, it may be precisely the differential changes in the relative supply of skilled and unskilled workers that explain both the presence of skill-replacing technical change in the nineteenth century and skill-biased technical change during the twentieth century.

A major shortcoming of the "pure technological" approaches—of both exogenous and endogenous varieties—is

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but simply because the effect of supply on technology is more important in understanding the questions posed above. I discuss below how supply may respond to changes in skill premia, and how this response may account for the joint behavior of the supply of, and demand for, skills over the past century.

that they do not provide a natural explanation for the fall in the wages of low-skill workers. Although a number of papers, including Caselli (1999), Greenwood and Yorukoglu (1997), and Galor and Moav (2000), show that technological revolutions may be associated with a fall in the wages of low-skill workers, it is difficult to see how sustained technological change can be associated with *an extended period* of falling wages of low-skill workers and stagnant average wages. This leads to the next question for this essay.

Why did the real wages of low-skill workers fall over the past several decades? There are a number of possible answers. First, labor-market institutions, for example labor unions, underwent important changes over the past thirty years, and these changes may have reduced the wages of many manufacturing workers, causing an increase in inequality and a decline in the real wages of low-skill workers (e.g., Richard Freeman 1991; John DiNardo, Nicole Fortin, and Lemieux 1995; David Lee 1999). Second, international trade between skill-scarce less-developed countries and skill-abundant rich economies increased over this period, and this may have put downward pressure on the wages of low-skill workers in the United States (e.g., Adrian Wood 1994; Edward Leamer 1995). Third, there has been a transformation of the way in which firms are organized, or perhaps in the way that firms and workers match (see, for example, Acemoglu 1999a; Michael Kremer and Eric Maskin 1999; Timothy Bresnahan 1997; Bresnahan, Erik Brynjolfsson, and Lorin Hitt 1999; and Autor, Frank Levy, and Richard Murnane 2000). Although each of these factors could have been the cause of the recent changes in the wage structure, I argue that their direct effect has been limited. Instead, I suggest that organizational change, labor-market institutions, and international trade have interacted with technical change in a fundamental way, amplifying the direct effect of technical change on inequality, and likely causing the decline in the wages of less-skilled workers.

Therefore, the overall picture that emerges is not necessarily one in which technology is the only factor affecting the distribution of income. On the contrary, the underlying thesis of this essay is that technology itself is no more than an endogenous actor. To explain the changes in the distribution of income, and to forecast what other changes may happen in the future, we need to understand the forces that shape technological progress, and how technology interacts with the overall organization of the labor market.

There is considerable uncertainty on many issues, and both more theoretical and more empirical work are needed. Two areas deserve special attention. The first is the differential behavior of residual inequality and returns to schooling during the 1970s. Most economists view changes in residual inequality as related to changes in labor-market prices. It is therefore puzzling that during the 1970s, while returns to schooling fell, residual and overall inequality increased. I argue below that models based on a single skill index (one type of skill or many types of skills that are perfect substitutes) are unable to explain this pattern. Instead, we need models with multidimensional skills. Moreover, for this type of model to explain the behavior of residual inequality during the 1970s and the 1980s, technological progress needs to have changed the demand for different types of skills differentially. The endogenous technology models discussed above provide a possible explanation for why different dimensions of skills may have been affected differentially by technical change. Nevertheless, the reasons for this type of behavior require much more research. More generally, we know relatively little about the determinants of residual inequality, and this topic is a major research area for the future. The second area is cross-country differences in the behavior of wage inequality. While inequality increased sharply in the United States, the United Kingdom, and Canada, it increased much less in Germany and many Scandinavian economies. Although there are a number of recent papers addressing these questions, much uncertainty still remains. I conjecture that cross-country differences in wage inequality may reflect, in part, technological choices made by these countries in response to the different incentives created by their labor-market institutions, but much more research on this topic is required.

2. *Empirical Trends*

The objective of this section is to illustrate a number of major inequality trends from the past several decades. My aim is not to offer a comprehensive survey of the empirical literature, but simply to highlight the most salient trends to anchor the theoretical discussion (see, e.g., Peter Gottschalk 1997; George Johnson 1997; Katz and Autor 2000, for recent surveys).

Figure 1 plots a measure of the supply of college skills between 1949 and 1995, constructed along the lines of Autor, Katz, and Krueger (1998), as the ratio of college equivalents (those with at least college + 0.5 × those with some college) to noncollege equivalents (those with high school or less + 0.5 × those with some college).[8] It also plots returns to college. This picture summarizes many of the salient trends I want to emphasize. In particular,

1. There has been a remarkable increase in the supply of skills in the U.S. economy over the past sixty years. In 1939, just over 6 percent of American workers were college graduates. By 1996 this number had increased to over 28 percent. In 1939, almost 68 percent of all workers did not have a high school degree. In 1996, this number had fallen to less than 10 percent (see, for example, Autor, Katz, and Krueger 1998, table 1). The relative supply of skills plotted in figure 1 provides a summary of these changes.

2. There has been no tendency for the returns to college to fall in the face of this large increase in supply—on the contrary, there is an increase in the college premium over this time period. An important issue is whether changes in the returns to college (or more generally other measures of wage inequality) correspond to true changes in the returns to skills. As is well-known in the labor literature, observed schooling premia may reflect returns to ability. This raises the possibility that changes in the returns to schooling may be driven by composition effects (changes in the composition of ability across schooling groups). In the appendix, I elaborate how changes in the distribution of unobserved skills across groups can create composition effects, and show that these composition effects cannot be responsible for the changes in the wage structure. Therefore, here I interpret these changes in the observed returns to schooling as changes in the true price of skills.

3. Following an acceleration in the supply of skills, returns to college fell sharply during the 1970s, leading Richard Freeman to conclude that "*Americans are over-educated*" (Freeman 1976). Returns to college then rose

[8] See the appendix for data details.

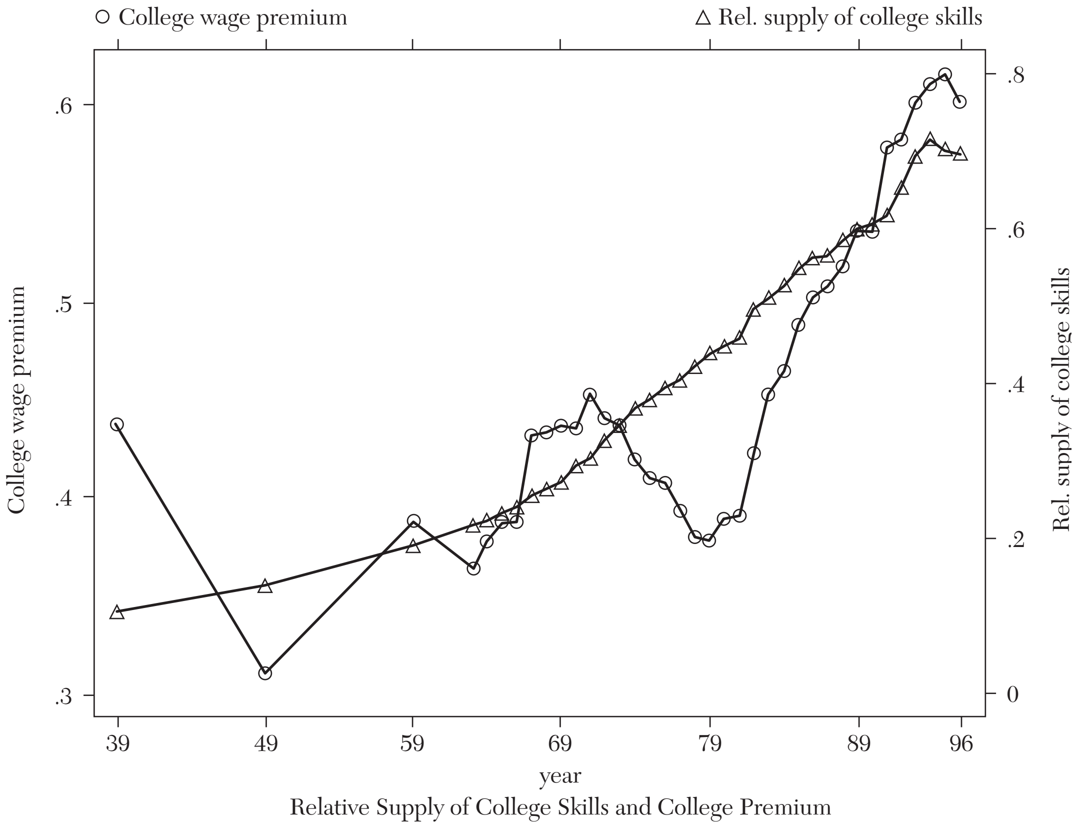

Figure 1. The Behavior of the (log) College Premium and Relative Supply of College Skills (weeks worked by college equivalents divided by weeks worked of noncollege equivalents) between 1939 and 1996. Data from March CPSs and 1940, 1950, and 1960 censuses.

very sharply during the 1980s. This increase in the returns to schooling has been one of the major motivating facts for the empirical inequality literature (e.g., Bound and Johnson 1992; Katz and Murphy 1992).

There have also been important changes in the overall distribution of wages. Figure 2 plots the 90th, 50th and 10th percentiles of the overall wage (weekly earnings) distribution for white male workers between 1963 and 1997 (with the 1963 values for all series indexed to 100).[9] This figure illustrates two more important patterns:

1. Overall wage inequality started to increase sharply in the early 1970s after a period of relative stability—prior to the 1970s, the 90th, 50th, and 10th percentiles of the wage distribution followed each other closely, but came apart sharply in the 1970s.

2. Median wages stagnated from 1975 onwards, while workers at the 10th percentile of the wage distribution (i.e.,

[9] Sample constructed as described in the appendix. I focus here on wage inequality for white men since labor market participation of women increased substantially over the sample period, and this would likely contribute to the composition effects. Moreover, male-female wage difference narrowed substantially over the same time period as well. School quality for black men also underwent significant transformation (e.g., Welch 1973; Card and Krueger 1992), and this could create significant composition effects.

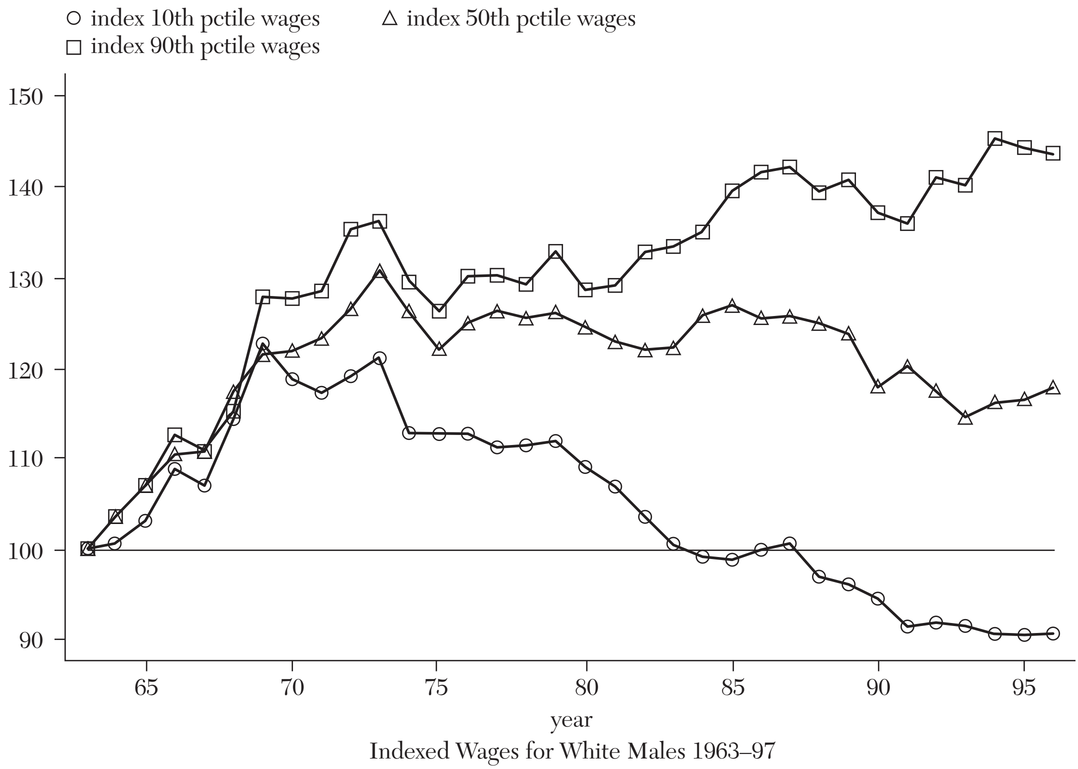

Figure 2. Changes in the Indexed Value of the 90th, 50th, and 10th Percentiles of the Wage Distribution for White Males (1963 values normalized to 100). Data from March CPSs.

"low-skill workers") saw their earnings fall in real terms to levels even below those in 1963.[10]

[10] Average wages, like median wages, have stagnated. For example, white men aged 30–49 earned 409 a week in 1999 dollars in 1949, and 793 in 1969, which corresponds approximately to a 3.4 percent a year increase in real wages between 1949 and 1969. In contrast, the same age group earned 909 in 1989, or experienced only a 0.6 percent a year increase between 1969 and 1989 (all numbers author's calculation from census data). The behavior of the median and average wage growth depends on the consumption deflator. I have followed the literature in using the personal consumption expenditure deflator. It has been argued that this deflator overstates inflation because of difficulties in measuring quality change (e.g., Michael Boskin et al. 1995). Even in the presence of such measurement problems, a large gap remains between the rate of increase of real wages before and after the 1970s, unless there is an "acceleration" in this bias exactly around the 1970s. Part of this gap is due to the increased importance of nonwage income and benefits. In fact, thanks to the increase in benefits, the share of labor in national income has not fallen over this period (see, e.g., Krueger 1999). So whether average wages have stagnated or continued to increase in line with output growth depends on how benefits are valued relative to earnings. It is also important to note that if these non-wage benefits are taken into account, inequality appears to have increased even more than the numbers here indicate (Brooks Pierce 2000). This is because high-wage workers are the primary recipients of such benefits.

Figure 3 turns to another measure: residual (within-group) inequality, which shows inequality among observationally equivalent workers. This figure displays three measures of residual inequality among white male workers between 1963 and 1997: 50–10, 90–50 and 0.5 times 90–10 log wage residual differentials (I plot 0.5 times 90–10 wage differentials in order to fit this on the same scale as the other measures).

Figure 3. 90–50, 50–10 and 0.5 × 90–10 Differentials from Log Weekly Wage Regressions for White Males Aged 18–65.

To calculate these measures, I look at the residuals from a standard Mincerian wage regression of the form

$$\ln w_{it} = X'_{it}\beta_t + v_{it}, \tag{1}$$

where w_{it} is weekly earnings for individual i observed in year t, and X_{it} is a set of controls which include nine education dummies, a quartic in experience, and region controls (constructed from the March CPSs; see the appendix for details of the sample). The fact that β_t is indexed by t indicates that returns to these observed characteristics are allowed to vary from year to year. The measures of residual inequality are calculated as the difference between the 90th and the 10th (or the 50th and the 10th, etc.) percentile values of the residual distribution from this regression, v_{it}. Residual inequality appears to have increased very much in tandem with overall inequality—it shows a sharp increase starting in the early 1970s.[11] Remarkably, all three measures of residual inequality behave very similarly, suggesting that forces affecting the top of the male wage distribution (90–50) are also affecting the bottom of the wage distribution (50–10). Finally, note an important contrast between figure 1 and figures 2 and 3. While returns to schooling fell during the 1970s, overall

[11] DiNardo, Fortin, and Lemieux (1995) provide evidence from the May Current Population Survey (CPS) data that residual and overall wage inequality started to increase in the 1980s. Katz and Autor (2000), on the other hand, find that residual wage inequality started to increase in the 1970s from March and May CPS data, and from census data. See the appendix. Recent work by Thomas Piketty and Emanuel Saez (2001) also finds an increase in inequality during the 1970s using data from the Internal Revenue Service tax returns.

and residual inequality increased. I return to this issue later in the essay.

3. *Introduction to the Theory of Skill Premia*

While, undoubtedly, many factors affect the distribution of wages, a natural starting point for an economic analysis is that of supply and demand. In the introduction to his pioneering study of income distribution, Tinbergen (1975, p. 15) wrote

> . . . what matters is the difference between qualities *available* and qualities *required* by the demand side, that is by the organization of production. (italics in original)

This is where I begin as well. I introduce a simple framework that links wages to supply of skills and to demand generated by the technology possibilities frontier of the economy. There are two types of workers, skilled and unskilled (high and low-education workers), who are imperfect substitutes. Imperfect substitution between the two types of workers is important in understanding how changes in relative supplies affect skill premia. For now I think of the unskilled workers as those with a high school diploma, and the skilled workers as those with a college degree.[12] So the focus in this section is on returns to schooling (or between-group inequality), and I use the terms "skill" and education interchangeably. In practice, education and skills are only imperfectly correlated, so it is useful to bear in mind that since there are skilled and unskilled workers within the same education group, an increase in the returns to skills will also lead to an increase in within-group inequality.

Suppose that there are $L(t)$ unskilled (low-education) workers and $H(t)$ skilled (high-education) workers, supplying labor inelastically at time t. All workers are risk neutral, and maximize (the present value of) labor income. Also suppose that labor markets are competitive (I return below to the role played by noncompetitive elements, especially in the European context).

The production function for the aggregate economy takes the constant elasticity of substitution (CES) form

$$Y(t) = [(A_l(t)L(t))^{\rho} + (A_h(t)H(t))^{\rho}]^{1/\rho}, \quad (2)$$

where $\rho \leq 1$, and $A_l(t)$ and $A_h(t)$ are factor-augmenting technology terms. Although all the results of interest hold for a general constant returns to scale $F(.)$ function, I focus on the CES production function to simplify the discussion. I drop the time argument when this causes no confusion.

The elasticity of substitution between skilled and unskilled workers in this production function is $\sigma \equiv 1/(1-\rho)$. I refer to skilled and unskilled workers as gross substitutes when the elasticity of substitution $\sigma > 1$ (or $\rho > 0$), and gross complements when $\sigma < 1$ (or $\rho < 0$). Three noteworthy special cases are: (i) $\sigma \to 0$ (or $\rho \to -\infty$) when skilled and unskilled workers will be Leontieff, and output can be produced only by using skilled and unskilled workers in fixed proportions; (ii) $\sigma \to \infty$ when skilled and unskilled workers are perfect substitutes, and (iii) $\sigma \to 1$, when the production function tends to the Cobb Douglas case. The value of the elasticity of substitution will play a crucial role in the interpretation of the results that follow. In particular, in this framework, technologies either increase the productivity of skilled or unskilled workers, that is, there are no explicitly skill-replacing or unskilled-labor-replacing

[12] This classification of workers into skilled and unskilled groups is obviously appropriate only for the twentieth-century United States. In many other countries or periods, high school graduates could be considered to be "skilled" workers. More generally, the two-skill model is a convenient simplification, less realistic than a world with a continuum of imperfectly substitutable skills.

technologies.[13] But, as we will see below, depending on the value of the elasticity of substitution, an increase in A_h can act either to complement or to "replace" skilled workers.

The production function (2) admits three different interpretations:

1. There is only one good, and skilled and unskilled workers are imperfect substitutes in the production of this good.

2. The production function (2) is also equivalent to an economy where consumers have utility function $[Y_l^\rho + Y_h^\rho]^{1/\rho}$ defined over two goods. Good Y_h is produced using only skilled workers, and Y_l is produced using only unskilled workers, with production functions $Y_h = A_h H$, and $Y_l = A_l L$. In this interpretation, it is important that the economy is closed. We will see in section 6.3 that different results obtain when international trade in these two goods is allowed.

3. A mixture of the above two whereby different sectors produce goods that are imperfect substitutes, and high- and low-education workers are employed in both sectors.

Although the third interpretation is more realistic, I generally use one of the first two, as they are easier to discuss. Since labor markets are competitive, the unskilled wage is

$$w_L = \frac{\partial Y}{\partial L} = A_l^\rho [A_l^\rho + A_h^\rho (H/L)^\rho]^{(1-\rho)/\rho}. \quad (3)$$

This equation implies $\partial w_L / \partial H/L > 0$: as the fraction of skilled workers in the labor force increases, the unskilled wage should increase. Similarly, the skilled wage is

$$w_H = \frac{\partial Y}{\partial H} = A_h^\rho [A_l^\rho (H/L)^{-\rho} + A_h^\rho]^{(1-\rho)/\rho},$$

which yields $\partial w_H / \partial H/L < 0$; everything else equal, as skilled workers become more abundant, their wages should fall. Combining these two equations, the skill premium—the wage of skilled workers divided by the wage of unskilled workers—is[14]

$$\omega = \frac{w_H}{w_L} = \left(\frac{A_h}{A_l}\right)^{\rho} \left(\frac{H}{L}\right)^{-(1-\rho)} \quad (4)$$
$$= \left(\frac{A_h}{A_l}\right)^{(\sigma-1)/\sigma} \left(\frac{H}{L}\right)^{-1/\sigma}.$$

Equation (4) can be rewritten in a more convenient form by taking logs,

$$\ln \omega = \frac{\sigma - 1}{\sigma} \ln \left(\frac{A_h}{A_l}\right) - \frac{1}{\sigma} \ln \left(\frac{H}{L}\right). \quad (5)$$

Naturally, the skill premium increases when skilled workers become more scarce, i.e.,

$$\frac{\partial \ln \omega}{\partial \ln H/L} = -\frac{1}{\sigma} < 0. \quad (6)$$

This is the usual substitution effect, and shows that for *given skill bias of technology*, as captured by A_h/A_l, the relative demand curve for skill is downward sloping with elasticity $1/\sigma = (1-\rho)$. Intuitively, an increase in H/L creates two different types of substitution. First, if

[13] A more general formulation would replace equation (2) with the production function

$$Y(t) = [(1-b_t)(A_l(t)L(t) + B_l(t))^\rho + b_t(A_h(t)H(t) + B_h(t))^\rho]^{1/\rho},$$

where B_l and B_h would be directly unskilled-labor-replacing and skill-replacing technologies, and an increase in b_t would correspond to some of the tasks previously performed by the unskilled being taken over by the skilled (see, e.g., Johnson and Stafford 1999 on this). For most of the analysis here, there is little to be gained from this more general production function (but see section 5.3).

[14] For some parameter values, skilled workers may have lower wages than the unskilled, i.e., $\omega \leq 1$. One may want to impose

$$\left(\frac{A_h}{A_l}\right)^{\sigma-1} > \frac{H}{L},$$

to avoid this. Alternatively, one could assume that skilled workers can use the technologies normally used by the unskilled, A_l, and be more (or equally) productive at this than the unskilled.

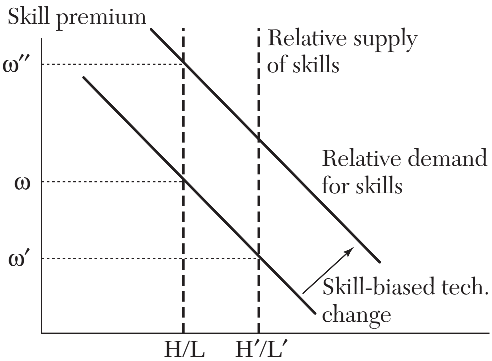

Figure 4. The Relative Demand for Skills

skilled and unskilled workers are producing the same good, but performing different functions, an increase in the number of skilled workers will necessitate a substitution of skilled workers for tasks previously performed by the unskilled. Second, if skilled and unskilled workers are producing different goods, the greater number of skilled workers will lead to a substitution of the consumption of the unskilled good by the skilled good. In both cases, this substitution hurts the relative earnings of skilled workers.

Figure 4 draws the relative demand for skills, equation (5), against the relative supply of skills, H/L, which is taken to be given for the purposes of this exercise. An increase in the relative supply, from H/L to H'/L', moves the equilibrium point along the downward sloping relative demand curve, and reduces the skill premium from ω to ω'.

An interesting case study of the response of the returns to schooling to an increase in the supply of skills is provided by the experience in the West Bank and Gaza Strip during the 1980s. As Joshua Angrist (1995) illustrates, there was a very large increase in the supply of skilled Palestinian labor as Palestinian institutions of higher education, totally absent before 1972, began to open. Angrist shows that premia to college graduate workers (relative to high school graduates) that were as high as 40 percent quickly fell to less than 20 percent. The extent of substitution was also clear. First, many college graduate workers could not find employment in skilled jobs: Angrist (1995) shows a sharp increase in the unemployment rate of college graduates, and Ze'ev Schiff and Ehud Ya'ari (1989) report that only one in eight Palestinian graduates could find work in his profession, with the rest working as unskilled laborers, mainly in the construction industry. Second, premia for tasks usually performed by more educated workers fell sharply. Between 1984 and 1987, the premium for administrative and managerial jobs (relative to manual laborers) fell from .32 to .12, while the premium for clerical workers fell from .02 to –.08 (see Angrist 1995 for details).

As equation (6) shows, the elasticity of substitution, σ, is important for the behavior of the skill premium when supply changes. The elasticity of substitution is also crucial for the response of the skill premium to changes in technology. Unfortunately, this parameter is rather difficult to estimate, since it refers to an elasticity of substitution that combines substitution both within and across industries. Nevertheless, there are a number of estimates using aggregate data that give a range of plausible values. The majority of these estimates are between $\sigma = 1$ and 2 (see for example Freeman 1986). The response of college premium for Palestinian labor reported in Angrist (1995), for example, implies an elasticity of substitution between workers with sixteen years of schooling and those with less than twelve years of schooling of approximately $\sigma = 2$.

Given the focus of this essay, it is also important to know how the skill premium responds to technology. Differentiation of (5) shows that the result depends on the elasticity of substitution:

$$\frac{\partial \ln \omega}{\partial \ln (A_h/A_l)} = \frac{\sigma - 1}{\sigma}.$$

Therefore, if $\sigma > 1$ (i.e., $\rho \in (0, 1]$), then improvements in the skill-complementary technology increase the skill premium. This can be seen in figure 4 as a shift out of the relative demand curve, moving the skill premium from ω to ω''. The converse is obtained when $\sigma < 1$: that is, when $\sigma < 1$, an improvement in the productivity of skilled workers, A_h, relative to the productivity of unskilled workers, A_l, shifts the relative demand curve in and reduces the skill premium. This case appears paradoxical at first, but is, in fact, quite intuitive. Consider, for example, a Leontieff (fixed proportions) production function. In this case, when A_h increases and skilled workers become more productive, the demand for unskilled workers increases by more than the demand for skilled workers. In some sense, in this case, the increase in A_h is creating an "excess supply" of skilled workers given the number of unskilled workers. This excess supply increases the unskilled wage relative to the skilled wage. This observation raises an important caveat. It is tempting to interpret improvements in technologies used by skilled workers, A_h, as "skill-biased." However, when the elasticity of substitution is less than 1, it will be advances in technologies used with unskilled workers, A_l, that increase the relative productivity and wages of skilled workers, and an increase in A_h relative to A_l will be "skill-replacing."

Nevertheless, the conventional wisdom is that the skill premium increases when skilled workers become relatively more—not relatively less—productive, which is consistent with $\sigma > 1$. In fact, as noted above, most estimates show an elasticity of substitution between skilled and unskilled workers greater than 1.

It is also useful to compute the average wage in this economy. Without controlling for changes in the educational composition of the labor force, the average wage is

$$w = \frac{Lw_L + Hw_H}{L + H} = \frac{[(A_l L)^\rho + (A_h H)^\rho]^{1/\rho}}{1 + H/L}, \quad (7)$$

which is also increasing in H/L as long as the skill premium is positive (i.e., $\omega > 1$ or $A_h^\rho (H/L)^\rho - A_l^\rho > 0$). Intuitively, as the skill composition of the labor force improves, wages will increase.

Therefore, the results so far imply that in response to an increase in H/L:

1. The relative wages of skilled workers, the skill premium $\omega = w_H/w_L$, decreases.
2. Wages of unskilled workers increase.
3. Wages of skilled workers decrease.
4. The average wage (without controlling for education) rises.

It is also useful to highlight the implications of an increase in A_h on wage levels. First, an increase in A_h, with A_l constant, corresponds to an increase in A_h/A_l; the implications of this change on the skill premium were discussed above. Moreover if A_h increases, everything else being equal, we expect both the wages of unskilled and skilled workers (and therefore the average wage) to increase: in this framework, technological improvements always increase all wages.

The most central result for our purposes is that as H/L increases, the skill premium, ω, should fall. In terms of figure 4, the increase in supply corresponds to a rightward shift in the vertical line from H/L to H'/L', which would move the economy along the downward sloping demand curve for skills. But this tendency of the skill premium to fall could be counteracted by changes in technology, as captured by

$\frac{\sigma - 1}{\sigma}$ ln (A_h/A_l). Therefore, this simple formulation encapsulates the essence of the two forces that Tinbergen (1975) emphasized:

> The two preponderant forces at work are *technological development*, which made for a relative increase in demand and hence in the income ratio . . . and *increased access to schooling*, which made for a relative decrease. (p. 35, italics in original)

As discussed in the empirical trends section, the past sixty years, and particularly the past thirty years, have witnessed a rapid increase in the supply of skills, H/L, but no corresponding fall in the skill premium. This implies that the demand for skills *must have increased*—as a result of Tinbergen's "technological development"—to prevent the relative wages of skilled workers from declining. Although in richer models there could be other factors leading to such a steady increase in the demand for skills, the cause highlighted by this simple framework, skill-biased technical change, is a natural candidate. More explicitly, the relative productivity of skilled workers, $(A_h/A_l)^{(\sigma - 1)/\sigma}$, must have increased.

The increase in $(A_h/A_l)^{(\sigma - 1)/\sigma}$ can be interpreted in a number of different ways. In a two-good economy, such skill-biased technical change corresponds to an increase in A_h/A_l and $\rho > 0$ $(\sigma > 1)$—i.e., skilled workers becoming more productive. Skill-biased technical change could also take the form of a decrease in A_h/A_l and $\rho < 0$ $(\sigma < 1)$. In this case the "physical" productivity of unskilled workers would increase, but their relative wages would fall due to relative price effects. Alternatively, with the one-good interpretation, skill-biased technical change simply corresponds to a change in the production function that increases $(A_h/A_l)^{(\sigma - 1)/\sigma}$.

Some back-of-the-envelope calculations provide a sense of the rise in A_h/A_l implied by the changes in the structure of wages and employment. Autor, Katz, and Krueger (1998) report employment and wage-bill shares for different groups of workers in their appendix table A1. If we assume a specific value for σ, we can translate these numbers into changes in A_h/A_l. In particular, notice that the relative wage bill of skilled workers is given by

$$S_H = \frac{w_H H}{w_L L} = \left(\frac{A_h}{A_l}\right)^{(\sigma - 1)/\sigma} \left(\frac{H}{L}\right)^{(\sigma - 1)/\sigma}. \quad (8)$$

Hence, we have

$$\frac{A_h}{A_l} = \frac{S_H^{\sigma/(\sigma - 1)}}{H/L}. \quad (9)$$

In table 1, I calculate the implied A_h/A_l values for $\sigma = 1.4$ and for $\sigma = 2$ using workers with some college, college graduates, and college equivalents definitions of Autor, Katz, and Krueger (1998)—see their paper for a more detailed analysis that controls for potential composition effects. In all cases, there is a large implied increase in A_h/A_l and $(A_h/A_l)^{(\sigma - 1)/\sigma}$. For example, the numbers indicate that, assuming an elasticity of substitution of 1.4, the relative productivity of college graduates, A_h/A_l, which was approximately 0.030 in 1960, increased to 0.069 in 1970, and to 0.157 in 1980. Between 1980 and 1990, it increased by a factor of almost three to reach 0.470. As equation (5) shows, changes in the demand index $D = (A_h/A_l)^{\frac{\sigma - 1}{\sigma}}$ may be more informative than changes in A_h/A_l, so table 1 also gives the evolution of D.

The view that the post-war period is characterized by skill-biased technical change also receives support from the within-industry changes in employment patterns. With constant technology, an increase in the relative price of a factor should depress its usage in all sectors. Since the college premium increased after 1979, with constant technology, there should be fewer college graduates

TABLE 1
EMPLOYMENT SHARES AND SKILL-BIASED TECHNICAL CHANGE, 1940–1990

	Employment Share			Wage Bill Share		
	Some college	College graduate	College equivalent	Some college	College graduate	College equivalent
1940	6.4	6.1	9.3	8.9	12.3	16.7
1950	9.5	7.7	12.4	11.0	11.9	17.4
1960	12.5	10.1	16.4	14.1	16.4	23.4
1970	16.4	13.4	21.5	16.5	21.5	29.7
1980	23.6	19.2	31.0	22.4	28.1	39.3
1990	30.8	24.0	39.3	28.5	36.7	51.0

	$\sigma = 1.4$						$\sigma = 2$					
	Some college		College graduate		College equivalent		Some college		College graduate		College equivalent	
	$\frac{A_h}{A_l}$	D	$\frac{A_h}{A_l}$	D	$\frac{A_h}{A_l}$	D	$\frac{A_h}{A_l}$	D	$\frac{A_h}{A_l}$	D	$\frac{A_h}{A_l}$	D
1940	0.004	0.21	0.016	0.31	0.035	0.38	0.140	0.37	0.303	.055	0.392	0.63
1950	0.006	0.24	0.011	0.28	0.030	0.37	0.146	0.38	0.219	0.47	0.313	0.56
1960	0.013	0.29	0.030	0.37	0.080	0.48	0.189	0.43	0.343	0.59	0.476	0.69
1970	0.017	0.32	0.069	0.47	0.179	0.61	0.199	0.45	0.485	0.70	0.652	0.81
1980	0.042	0.40	0.157	0.59	0.486	0.81	0.270	0.52	0.643	0.80	0.933	0.97
1990	0.090	0.50	0.470	0.81	1.777	1.18	0.357	0.60	1.064	1.03	1.673	1.29

Note: The first panel gives the ratio of the employment of skilled relative to unskilled workers, and the wage bill of skilled to unskilled workers for the corresponding skill categories. These data are taken from Autor, Katz, and Krueger (1998). Some college refers to those with more than high school (hence the measure is those with more than high school divided by those with high school or less). College graduate refers to all those with a college degree, and college equivalent is defined, as in Autor et al., as those with a college degree + 0.5 × those with some college (correspondingly, the unskilled are defined as those with high school and less + 0.5 × those with some college). The bottom panel gives the implied technology shifts using equation (9) above for different values of the elasticity of substitution. The demand index D is defined as $(A_h/A_l)^{\frac{\sigma-1}{\sigma}}$.

employed in all sectors—and the sectoral composition should adjust in order to clear the market. The evidence is very much the opposite. Berman, Bound, and Griliches (1994) and Murphy and Welch (1993) show a steady increase in the share of college labor in all sectors.

This discussion leads to my first conclusion, which I highlight for future reference.

Conclusion 1. The past sixty years must have been characterized by skill-biased technical change.

Furthermore, Goldin and Katz (1998) provide evidence of technology-skill complementarity during the 1910s and 1920s. In light of this evidence, one might consider the bulk of the twentieth century to have been characterized by skill-biased technical change, though whether technical change during the early twentieth century was or was not skill-biased is not central for the focus of this paper.

4. *Steady-Demand and Acceleration Hypotheses*

The previous section highlighted the importance of skill-biased technical change over the past several decades. A first hypothesis is that skill-biased technical change takes place steadily—at a constant pace—over time. Alfred Marshall begins *The Principles of Economics* by reiterating the eighteenth-century taxonomist Carl Linneaus' motto that "Nature does not make leaps." It is also natural in this context to begin with a hypothesis in which skill-biased technical change does not make jumps, but progresses steadily. The alternative would be a process that is at times more skill-biased than others—or even unskill-biased during some episodes. In this section, I contrast the steady-demand hypothesis, which maintains that skill-biased technical change has progressed at a constant pace over the post-war period, against the acceleration hypothesis, which sees a break with past trends in recent decades.

4.1 *Steady-Demand Hypothesis*

According to this hypothesis, there has been no major change in the structure of demand for skills. Versions of this story have been suggested by Freeman (1976), and it has been proposed as an explanation for the changes in the wage structure during the 1970s and the 1980s by Katz and Murphy (1992), and more recently by Murphy, Riddell, and Romer (1998) and Card and Lemieux (2000).

In a simple form, this hypothesis can be captured by writing

$$\ln\left(\frac{A_h(t)}{A_l(t)}\right) = \gamma_0 + \gamma_1 t, \tag{10}$$

where t is calendar time. Substituting this equation into (5), we obtain

$$\ln \omega = \frac{\sigma - 1}{\sigma}\gamma_0 + \frac{\sigma - 1}{\sigma}\gamma_1 t - \frac{1}{\sigma}\ln\left(\frac{H}{L}\right). \tag{11}$$

It is useful to link this equation to the two forces discussed above, and emphasized by Tinbergen (1975). According to equation (11), "technological developments" take place at a constant rate, but the supply of skilled workers could grow at different rates. Therefore, changes in the returns to skills are caused by uneven growth in the supply of skills. When H/L grows faster than the rate of skill-biased technical change, $(\sigma - 1)\gamma_1$, the skill premium will fall. And when the supply growth falls short of this rate, the skill premium will increase. The story has obvious appeal because the 1970s, when returns to schooling fell sharply, were a period of faster than usual increase in the supply of college graduate workers as figure 1 and table 1 show. In contrast, the 1980s were a period of slow increase in the supply of skills relative to the 1970s. Katz and Murphy (1992) estimate a version of equation (11) above using aggregate data between 1963–87.[15] They find

$$\ln \omega = \underset{(0.01)}{0.033 \cdot t} \quad \underset{(0.15)}{-0.71} \cdot \ln\left(\frac{H}{L}\right)$$

This approach does fairly well in capturing the broad features of the changes in the college premium between 1963 and 1987. The predicted values from the above equation are quite close to the observed movements in the college premium, suggesting that the U.S. labor market since 1963 can be characterized by an elasticity of substitution between college graduate workers and noncollege workers of about $\sigma = 1/0.71 \approx 1.4$, and an annual increase in the demand for skills at the rate of about 3.3 percent (or $\gamma_1 \approx \frac{\sigma}{\sigma-1} \cdot 0.033 \approx 0.115$). The increase in the college premium during the 1980s is then explained by the slowdown in the

[15] They use the relative supply of college equivalent workers. This is defined as college graduates + 0.29 × some college – 0.05 × high school dropouts divided by high school graduates + 0.69 × some college + 0.93 × high school dropouts.

growth rate of the supply of college graduate workers.

Nevertheless, there are a number of reasons for preferring a cautious interpretation of this regression evidence. The regression uses only 25 aggregate observations, and there is significant serial correlation in the college premium (as also noted by Katz and Murphy). If the true data were generated by an acceleration in skill bias and a larger value of the elasticity of substitution, this regression could estimate a smaller elasticity of substitution and no acceleration in the demand for skills (see below on this). For example, Katz and Murphy show that if the true elasticity of substitution is $\sigma = 4$, a significant acceleration in the skill bias of technical change is required to explain the data. Moreover, from the wage-bill share data reported above, Autor, Katz, and Krueger (1998) conclude that even for the range of the values for the elasticity of substitution between $\sigma = 1$ and 2, skill-biased technical change is likely to have been more rapid during the 1980s than the 1970s. This can also be seen in table 1 above, where, for most measures, the increase in $(A_h/A_l)^{\frac{\sigma-1}{\sigma}}$ appears much larger between 1980 and 1990 than in other decades. We therefore need to discuss more detailed evidence on this issue.

4.2 *Evidence on Steady-Demand versus Acceleration*

The first piece of evidence often put forth in support of an acceleration relates to the role of computers in the labor market. Krueger (1993) argued that computers changed the structure of wages, and showed that workers using computers are paid more, and this computer wage premium has increased over time. Although this pattern is striking, it is not particularly informative about the presence or acceleration of skill-biased technical change. It is hard to know whether the computer wage premium is for computer skills, or whether it is even related to the widespread use of computers in the labor market. For example, DiNardo and Jorn-Steffen Pischke (1997), Horst Enthorf and Francis Kramartz (1998) and Lex Borghans and Bas Ter Weel (2000) show that the computer wage premium is likely to be a premium for unobserved skills.[16]

The second set of evidence comes from the cross-industry studies of, among others, Berman, Bound, and Griliches (1994), Autor, Katz and Krueger (1998), and Stephen Machin and John Van Reenan (1998). These papers document that almost all industries began employing more educated workers during the 1970s and the 1980s. They also show that more computerized industries experienced more rapid *skill upgrading*, i.e., they increased their demand for college-educated workers more rapidly. For example, Autor, Katz, and Krueger run regressions of changes in the college wage-bill share in three-digit industries on computer use between 1984 and 1993. They find:

$$\underset{}{\Delta Sc_{80-90}} = \underset{(.108)}{.287} + \underset{(.046)}{.147} \cdot \Delta cu_{84-93}$$

$$\Delta Sc_{90-96} = \underset{(.196)}{-.171} + \underset{(.081)}{.289} \cdot \Delta cu_{84-93}$$

where ΔSc denotes the annual change in the wage-bill share of college graduates in that industry (between the indicated dates), and Δcu_{84-93} is the increase in the fraction of workers using computers in that industry between 1984 and 1993. These regressions are informative since

[16] Equally, however, it would be wrong to interpret the findings of DiNardo and Pischke (1997) and Enthorf and Kramartz (1998) as evidence against an acceleration in skill-biased technical change, since, as argued below, such technical change would increase the market prices for a variety of skills, including unobserved skills.

the college wage-bill share is related to the demand for skills as shown by equation (9). The results indicate that in an industry where computer use increased by 10 percent, the college wage-bill share grew by about 0.15 percent *a year* faster between 1980 and 1990, and 0.3 percent faster *a year* between 1990 and 1996.

Although this evidence is suggestive, it does not establish that there has been a change in the trend growth of skill-biased technology. As pointed out in conclusion 1 above, the only way to make sense of the post-war trends is to incorporate skill-biased technical change over the whole period. Moreover, Goldin, and Katz (1998) present evidence suggesting that capital-skill complementarity may have been as high during the 1910s as during the recent period because of increased demand for skills coming from the introduction of electricity in most manufacturing processes. Similarly, even though there were few computers in workplaces before the 1970s, other technological developments may have increased the demand for skills as rapidly as—or more rapidly than—computers. Therefore, the question is whether computers and the associated information technology advances increased the demand for skills *more* than other technologies did during the 1950s and the 1960s, or even earlier. This question *cannot be answered* by documenting that computerized industries demand more skilled workers.[17]

Cross-industry studies also may not reveal the true impact of computers on the demand for skills, since industries that are highly computerized may demand more skilled workers for other reasons as well.[18] In fact, when Autor, Katz, and Krueger (1998) run the above regressions for the 1960–70 college wage-bill shares, they obtain

$$\Delta Sc_{60-70} = \underset{(.058)}{.085} + \underset{(.025)}{.071} \cdot \Delta cu_{84-93}.$$

Therefore, industries investing more in computers during the 1980s were already experiencing more skill upgrading during the 1960s, before the spread of computers (though perhaps slower than after the 1980s, since the coefficient here is about half of that between 1980 and 1990). This suggests that at least part of the increase in the demand for skills coming from highly computerized industries may not be the direct effect of computers, but reflect a secular long-run shift toward more skilled workers. So faster skill upgrading by highly computerized industries is not inconsistent with the steady-demand hypothesis.

The third, and probably most powerful, piece of evidence in favor of an acceleration in skill bias also comes from Autor, Katz, and Krueger (1998). They document that the supply of skills grew faster between 1970 and 1995 than between 1940 and 1970—by 3.06 percent a year during the latter period compared to 2.36 percent a year during the earlier thirty years. In contrast, the college premium increased between 1970 and 1995 by about 0.39 percent a year, while it fell by about 0.11 percent a year during the earlier period. If demand for skills had increased at a steady pace, the college premium should have

[17] This argument is related to a point first raised by Lawrence Mishel and Jared Bernstein (1994). They pointed out that much of the evidence presented in favor of the impact of technology on inequality shows that there has been skill-biased technical change during the 1980s, *not* that skill-biased technical change has *accelerated* relative to earlier periods.

[18] Mark Doms, Timothy Dunne, and Kenneth Troske (1997) show that new technologies (but not computers) are adopted by plants that have more skilled and more highly paid workers, and these plants do not increase their wages or demand for skills after the implementation of these technologies.

also fallen since 1970.[19] Moreover, Autor, Katz, and Krueger (1998) document greater within-industry skill upgrading in the 1970s, 1980s, and 1990s than in the 1960s, which is also consistent with more rapid skill-biased technical change during these later decades.

A simple regression analysis also confirms this point. I combined the data from the March CPSs and decennial censuses used in figure 1 above. Using these data, a regression similar to that of Katz and Murphy for the period 1939–96 yields similar results:

$$\ln \omega = \underset{(0.01)}{0.025} \cdot t \quad - \underset{(0.20)}{0.56} \cdot \ln\left(\frac{H}{L}\right),$$

with an R^2 of 0.63 and an implied elasticity of substitution of 1.8, which is somewhat larger than the estimate of Katz and Murphy. However, adding higher order terms in time (i.e., time squared, time cubed, etc.) improves the fit of the model considerably, and these higher-order terms are significant. In figure 5, I plot the implied time trends from regressions with higher-order terms as well as the linear trend (all numbers were rescaled to fit in one graph). All three of these more flexible time trends show an acceleration in the relative demand for skills during the 1970s or the 1980s (the cubic and quartic time trends are almost identical, hence practically indistinguishable in the figure).

A fourth piece of evidence comes from Greenwood and Yorukoglu (1997) and Per Krusell et al. (2000). These authors argue, based on the work of Griliches (1969), that equipment capital is more complementary to skilled workers than unskilled workers. This premise may be reasonable since advances in equipment often appear to substitute machines for tasks previously performed by unskilled workers. Following the work by Robert Gordon (1990) and Greenwood, Zvi Hercowitz, and Krusell (1997), these papers document that the post-war period has witnessed a secular decline in the relative price of equipment capital, and argue that the associated increase in the stock of equipment capital led to skill-biased technical change. Moreover, they argue that this relative decline accelerated in the early 1970s, and the associated acceleration in the stock of equipment capital increased the demand for skills.

Krusell et al. (2000) formalize their approach by assuming the following production function:

$$Y = K_s^{\alpha}[b_1 L^{\mu} + (1 - b_1)(b_2 K_e^{\lambda} + (1 - b_2)H^{\lambda})^{\mu/\lambda}]^{(1-\alpha)/\mu}$$

where K_s is structures capital (such as buildings), and K_e is equipment capital (such as machines). The parameter $\sigma_1 = 1/(1 - \lambda)$ is the elasticity of substitution between equipment and skilled workers, and $\sigma_2 = 1/(1 - \mu)$ is the elasticity of substitution between unskilled workers and the equipment-skilled worker aggregate. If $\sigma_1 > \sigma_2$ (i.e., $\mu > \lambda$), equipment capital is more complementary to skilled workers than unskilled workers, and an increase in K_e will

[19] The college premium fell between 1940 and 1970 in part because it is estimated to be very high in the 1940 census. There may be reasons to be suspicious of data quality from this census, because (i) the education variable was different, (ii) there may have been an overstatement of years of schooling, possibly by as much as a factor of 1.5 or 2 for some cohorts, and (iii) there was no self-employment income in this census. But it is not clear whether any of these measurement problems will cause an upward bias in the college premium. In any case, the level of the college premium from this census is not out of line with other historical evidence (see, e.g., Goldin and Katz 2000; and Piketty and Saez 2001). Moreover Autor, Katz, and Krueger show that even ignoring data from the 1940 census, there is evidence for an acceleration in the skill bias of technical change. For example, for the range of the values for the elasticity of substitution between $\sigma = 1$ and 2, skill-biased technical change appears more rapid during the 1980s than in the 1970s and the 1960s.

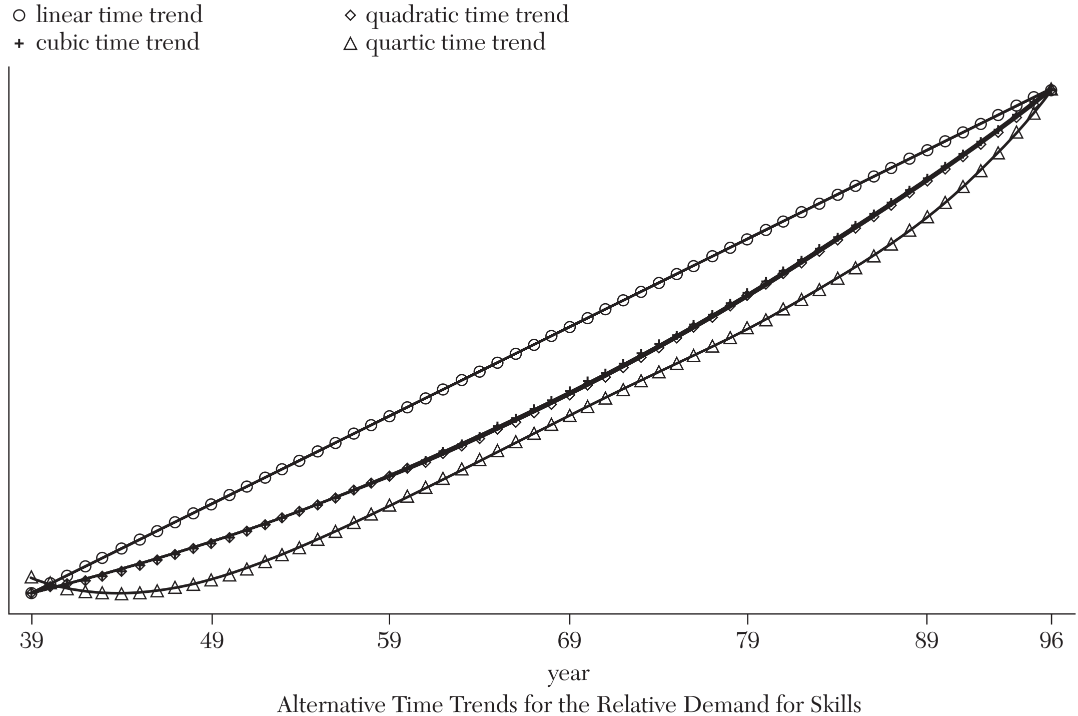

Figure 5. Estimates of Time Trends from Regressions of ln ω on ln (*H/L*), *year*, *year*^{2}, *year*^{3} and *year*^{4} between 1939 and 1996 (with observations in 1939, 1949, 1959 from the decennial censuses and observations for 1963–96 from the March CPSs)

increase the wages of skilled workers more than the wages of unskilled workers. More formally, the skill premium in this model is

$$\omega = \frac{w_H}{w_L} = \frac{(1-b_2)(1-b_1)H^{\lambda-1}(b_2K_e^{\lambda} + (1-b_2)H^{\lambda})^{(\mu-\lambda)/\lambda}}{b_1L^{\mu-1}}. \quad (12)$$

Differentiation of (12) shows that as long as $\mu > \lambda$, which corresponds to equipment capital being more complementary to skilled workers than unskilled workers, we have $\partial\omega/\partial K_e > 0$. So provided that equipment capital is more complementary to skilled workers than unskilled workers, an increase in the quantity of equipment capital will increase the demand for skills. Since the post-war period has been characterized by a decline in the relative price of equipment goods, there will be an associated increase in the quantity of equipment capital, K_e, increasing the demand for skills steadily.

Figure 6, which plots the log of this relative price series, shows the faster proportional decline after the 1970s. The behavior of the relative price series then suggests that there may have been an acceleration in the substitution of equipment capital for labor, causing more rapid skill-biased technical change.

Nevertheless, because there are serious difficulties in adjusting capital prices for quality, we may want to be cautious in interpreting this evidence. Another problem comes from the fact that, as I discuss in more detail below, a variety of other evidence does not support the notion of faster technological progress since 1974, which is a basic

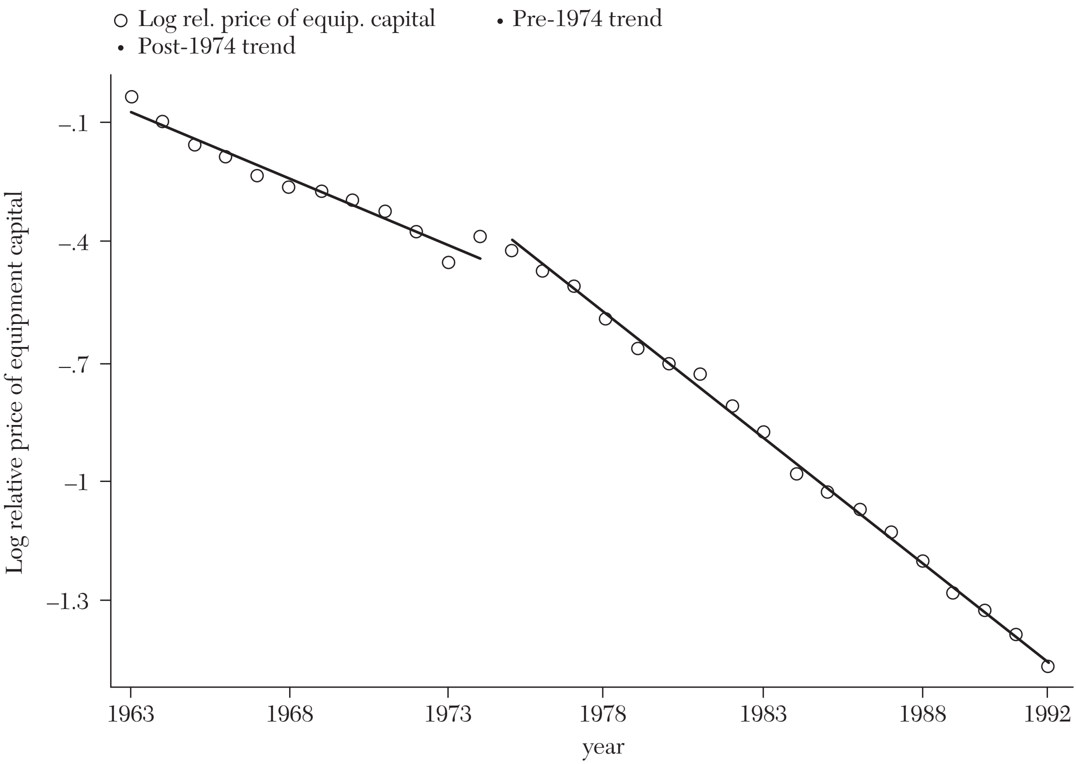

Figure 6. Behavior of the Log Relative Price of Equipment Capital, 1963–92

tenet of this approach. Finally, one would presume that if, in fact, the decline in the relative price of equipment capital is related to the increase in the demand for skills, then in a regression of equation (11), it should proxy for the demand for skills and perform better than a linear time trend. Table 2 reports a series of regressions which show that, on the contrary, the level or the log of the relative price of equipment capital is not significant in such regressions. Column 1 shows the equivalent of the regression by Katz and Murphy (1992) with only a time trend and the relative supply of skills. Columns 2 and 3 show regressions that replace the time trend with the level and log of the relative price of equipment capital. These terms are significant, but the fit of the regression is worse than the one in column 1. The remainder of the table shows that once these terms are entered simultaneously with the time trend, the time trend is significant, while there is no evidence that the relative price of equipment capital matters for the demand for skills. While this evidence may simply reflect the fact that the relative price of equipment is measured with error, it casts some doubt on the view that the relative price of equipment capital is directly linked to the demand for skills and that its faster decline since the 1970s indicates an acceleration in skill bias.

A final piece of evidence for acceleration comes from the behavior of overall and residual inequality over the past several decades. The sharp rise in both overall and residual wage inequality since the early 1970s, documented in

TABLE 2
THE EFFECT OF THE RELATIVE PRICE OF EQUIPMENT ON SKILLED PREMIA

Dependent variable is log college premium	(1)	(2)	(3)	(4)	(5)
Relative supply	–0.742 (0.053)	–0.388 (0.037)	–0.610 (0.068)	–0.691 (0.100)	–0.740 (0.054)
Time	0.026 (0.002)			0.022 (0.007)	0.024 (0.005)
Log relative price		–0.323 (0.024)		–0.051 (0.084)	
Relative price			–0.875 (0.086)		–0.056 (0.167)
Adjusted R^2	0.900	0.864	0.795	0.898	0.897

Note: This table reports the regression of the log college premium on a linear time trend, the log relative supply of skilled workers and various measures of the relative price of equipment capital. For comparability, all data taken from Krusell et al. (2000).

section 2, weighs in favor of a marked change in labor market prices and demand for skills during recent decades. This argument is based on the view that changes in residual inequality reflect changes in labor market prices, a thesis put forth by Chinhui Juhn, Murphy, and Brooks Pierce (1993).[20] This view is important for an interpretation for the recent changes in wage structure for two reasons. First, as the evidence in section 2 indicates, much of the recent increase in overall inequality is due to the rise in residual inequality. If residual inequality were unrelated to the demand and supply of skills, the framework here could only account for a relatively small fraction of the increase in overall inequality. The Juhn-Murphy-Pierce view, instead, suggests that the increase in residual inequality and the bulk of the rise in overall inequality are related to changes in labor market prices, and therefore to the supply and demand for skills. Second, according to this view, the rise in residual inequality is an important piece of evidence in the debate on acceleration: residual inequality, which was stable during the 1960s, began to increase rapidly during the early 1970s (figures 2 and 3), indicating a discontinuity in labor market prices and, most likely, in the rate of increase of the demand for skills.

A concrete example is useful for clarifying why residual inequality is linked to labor market prices. Suppose that two otherwise identical individuals differ in terms of their unobserved skills (for example, in terms of interpersonal skills, motivation, specific skills for their job, or IQ).[21] Denote the unobserved

[20] Of course, an alternative—and more cynical—view would be to interpret residual inequality as "a measure of our ignorance" (as Moses Abramovitz 1957 did for TFP). When a standard wage regression such as (1) provides a good fit, the residuals will be less disperse. Nevertheless, given the variety of skills that we are unable to measure in standard data sets, much of the residual will plausibly reflect rewards to some unobserved skills.

[21] By unobserved skills, I mean skills that are not observed by the econometrician. These skills could be—and are likely to be—observed by employers. These types of skills are often referred to

skill of individual 1 by a_1 and that of individual 2 by $a_2 > a_1$, and assume that wages are given by

$$\ln w_{it} = 2\theta_t a_i + \gamma_t h_i, \qquad (13)$$

where γ_t is the price of h skills at time t, while θ_t is the price of a skills. Since these individuals are identical in all respects other than their unobserved skills, a, we have the variance of log wages (or of residual wages) among these two individuals as:

$$Var(\ln w) = \theta_t^2(a_2 - a_1)^2.$$

Now if at a later date, t', this variance increases to $Var(\ln w)'$, and we know that these two individuals are still identical in all other respects and that $a_2 - a_1$ has not changed, we can interpret the increase in $Var(\ln w)$ as reflecting an increase in the price of unobserved skills, θ_t. The discussion in the appendix shows that the bulk of the increase in overall and residual inequality cannot be explained by composition effects, i.e., by changes in $a_2 - a_1$, so this increase is most likely due to a rise in the price of and demand for unobserved skills during the 1970s.[22] Therefore, with this interpretation, the rapid rise in the residual inequality during the 1970s and the 1980s indicates a more rapid increase in demand for skills during these decades than earlier.

Overall, there is a variety of evidence suggesting an acceleration in skill bias over the past 25–30 years. Although not all evidence is equally convincing, the rise in the returns to schooling over the past thirty years, despite the very rapid increase in the supply of skills, and the behavior of overall and residual inequality since the 1970s suggest a marked shift in the demand for skills over the past several decades. I therefore *tentatively* conclude:[23]

Conclusion 2. The behavior of returns to schooling and residual inequality over the past three decades suggests an acceleration in the demand for skills beginning in the 1970s or 1980s.

5. *Acceleration in Skill Bias*

What explains the more rapid increase in the demand for skills over the past several decades? The first possibility is a change in labor market institutions. The second is the role of increased international trade. The third is more rapid skill-biased technical change. I argue in section 6 that changes in labor market institutions and the increased importance of international trade cannot explain the change in labor market prices by themselves. Moreover, the evidence discussed in section 4 is consistent with new technologies playing an important role in changing the wage structure. So here I begin with changes in technologies, and in particular, I discuss "pure technological" approaches where technology is the only factor determining the demand for skills.

5.1 *"Technological Revolutions" and Acceleration in Skill Bias*

The first group of technological theories links the acceleration in skill bias to exogenous technological developments, and argues that a "technological revolution" led to more rapid skill-biased technical change beginning in the 1970s

as "unobserved ability." This does not imply that these unobserved skills are necessarily synonymous with IQ or other single dimensional skill indices.

[22] Put differently, the absence of large composition effects indicates that the rise in residual inequality likely reflects changes in the demand for unobserved skills rather than changes in the "supply of unobserved skills."

[23] The most important caveat is that the available data suggest relatively slow skill-biased technical change during the second half of the 1990s (see Mishel, Bernstein, and John Schmitt 1998; and Murphy and Welch 2000).

or the 1980s. In terms of the model developed above, this corresponds to a more rapid increase in A_h/A_l during this period, translating into greater skill premia. Many of the proponents of this view argue that the acceleration in skill bias is, at least in part, related to information technology and computers (for example, Krueger 1993; Berman, Bound, and Griliches 1994; Autor, Katz, and Krueger 1998; Berman, Bound, and Machin 1998).

An interesting version of this story is the one developed by Krusell et al. (2000) discussed above. They argue that the demand for skills accelerated as a result of the more rapid decline in the relative price of capital equipment beginning in the early 1970s.[24] The Krusell et al. theory is attractive since it provides a unified framework in which we can identify both the cause of the steady increase in the demand for skills, and the source of the more rapid skill-biased technical change, though the evidence provided in the previous section casts some doubt on the link between the relative price of equipment and the demand for skills.

The main idea of all these theories of acceleration is that new technologies are more complementary to skilled workers than to unskilled workers—for example, there are more rapid advances in the technologies used by skilled workers, as captured by A_h above. Rapid technological progress then corresponds to an *acceleration in skill bias*. An alternative perspective, building on an idea originally suggested by Nelson and Phelps (1966), also focuses on the effect of rapid technical change on inequality, but puts the emphasis on the ability of skilled workers to deal with the introduction of new technologies. According to this view, demand for skills will automatically increase during periods of rapid technological change. Welch (1970) gave an early succinct summary of these two views. The first view, which we may call the *acceleration hypothesis*, sees human capital as a factor of production, and the more rapid increase in the demand for skills results from an acceleration in technical change that favors this factor of production. In other words:

> [T]echnical change may not be neutral between skill classes. It may be that increments in technology result in increments in the relative productivity of labor that are positively related to skill level. (Welch 1970, p. 38)

In contrast, the second view—*the Nelson-Phelps hypothesis*—argues that[25]

[24] I classify this approach as one of exogenous technology, since the driving force, the decline in the relative price of equipment capital, is assumed exogenous.

An alternative interpretation of the approach by Krusell et al. (2000) is that the main determinant of the demand for skills is not technology-skill complementarity, but capital-skill complementarity. I believe that the distinction between technology-skill versus capital-skill is not very useful. Capital-skill complementarity could play an important role only in a model as in Greenwood et al. (1997) or Krusell et al. (2000), where new capital embeds superior technologies. In this sense, it is a combination of new capital and new technologies that is increasing the demand for skills. Moreover, Autor, Katz, and Krueger (1998) show that demand for more educated workers across industries is affected by high-tech capital (e.g., computers), but not by equipment capital, suggesting further that it is new technologies, not simply capital intensity, that matters for inequality.

[25] A recent paper by Samuel Bowles, Herbert Gintis, and Melissa Osborne (2001) has a similar classification of different approaches. They call the first view Walrasian, and the second Schumpeterian. In the first, skills that enable workers to produce more are valued, while in the second, it is skills that enable workers to deal with changes in economic and social environments. They also propose an alternative, Coasian, view, where "skills" are workers' capacity to work within organizations and follow authority. From the point of view of the analysis here, this view is not fundamentally different from the Walrasian view, since workers are paid more for skills that increase their marginal contribution to the profits of their employers.

> [T]he productivity of education would be positively related to the rate of change in useful technology (the ability to change) and to the size of the technological gap (room for innovation). In this case, if the rate of utilization of technology is accelerating, or if the technology gap is growing, the return to education will rise relative to other inputs. (p. 38)

Studies building on the Nelson-Phelps hypothesis include Galor and Tsiddon (1997), Greenwood and Yorukoglu (1997), Caselli (1999), Aghion and Howitt (1998, ch. 9), Galor and Moav (2000), Violante (2000), Rubinstein and Tsiddon (1999), Aghion, Howitt and Violante (2000), and Gould, Moav and Weinberg (2000).[26] These papers argue that there has been a technological revolution in the U.S. economy starting in the 1970s and relate the rise in inequality to the increased demand for skills resulting from the technological revolution. For example, Greenwood and Yorukoglu (1997) draw a parallel between the First and the Second Industrial Revolutions and what has been happening in the U.S. economy since 1974. Caselli (1999) develops a similar theory where a technological revolution increases the demand for workers who can switch to the sectors that benefit from the introduction of new technologies.[27]

To get a basic understanding of these approaches, it is useful to consider a simple model based on Galor and Moav (2000). Suppose that

$$A_l = \phi_l(g)a \text{ and } A_h = \phi_h a \tag{14}$$

where a is a measure of aggregate technology, and g is the growth rate of a, i.e., $g \equiv \dot{a}/a$. The presumption that skilled workers are better equipped to deal with technological progress can be captured by assuming that $\phi'_l < 0$. Galor and Moav (2000) refer to this assumption as the "erosion effect," since it implies that technical change erodes some of the established expertise of unskilled workers, and causes them to benefit less from technological advances than skilled workers do. Substituting from (14) into (4), the skill premium is

$$\omega = \frac{w_H}{w_L} = \left(\frac{A_h}{A_l}\right)^{(\sigma-1)/\sigma} \left(\frac{H}{L}\right)^{-1/\sigma} = \left(\frac{\phi_h}{\phi_l(g)}\right)^{(\sigma-1)/\sigma} \left(\frac{H}{L}\right)^{-1/\sigma}. \tag{15}$$

Therefore, as long as $\phi'_l < 0$, more rapid technological progress, as captured by a higher level of g, will increase the skill premium.

Theories that explain the increase in inequality as a result of rapid technological progress have a number of attractive features.[28] First, many economists and commentators view the advances in computer and information technology as a break with the technologies of the past, and so are open to

[26] See Aghion (2001) for an approach that combines the Nelson-Phelps insights with the Schumpeterian notion of creative-destruction to discuss the impact of the diffusion of computers on inequality.

[27] The explanation offered by Rubinstein and Tsiddon (1999), and Aghion, Howitt, and Violante (2000) is somewhat different. They argue that there is increased uncertainty at times of rapid technological change, and more skilled workers are better able to cope with uncertainty. This idea is also related to a thesis first put forth by Michael Piore and Charles Sabel (1984) that the oil price shocks increased the uncertainty faced by producers, and induced them to change the organization of production toward organizational forms that require adaptable workers.

[28] These theories also predict that inequality should increase when new technologies are being introduced, but should decline when these new technologies are standardized and being used routinely by many firms (see, for example, Galor and Tsiddon 1997, or Aghion, Howitt, and Violante 2000). So far, there seems to be no evidence of a decline in inequality in the United States, but perhaps the years to come will see a return to the levels of inequality experienced during the 1960s, vindicating this approach.

the idea that we might be in the midst of a technological revolution. Second, a variety of evidence supports the notion that skilled workers have a comparative advantage in coping with rapid technical change. Ann Bartel and Frank Lichtenberg (1987) show that firms introducing new technologies hire more skilled workers. Bartel and Nachum Sicherman (1998) document that returns to unobserved ability appear to be higher in industries with more rapid technical change. Andrew Foster and Mark Rosenzweig (1996) provide evidence from developing countries that more educated workers are better placed to take advantage of advances in agricultural technology.

The main difficulty with both the theories based on the acceleration and the Nelson-Phelps hypotheses is that they rely explicitly on rapid technical change in recent decades.[29] There is little direct evidence that the decades between 1970 and 1995 have been a period of rapid technical change, however. First, this period has experienced sluggish TFP and output growth relative to earlier periods. Greenwood and Yorukoglu (1997) and Hornstein and Krusell (1996) argue that the slow TFP growth itself may be an outcome of the more rapid technical change. According to this argument, new revolutionary technologies first reduce productivity growth as firms and workers spend time learning to use these technologies.

It is difficult to imagine how a new and radically more profitable technology will first lead to 25 years of substantially slower growth. Although, in an influential paper, Paul David (1990) argues that the spread of electricity to American manufacturing was also slow and productivity gains from electrification were limited until the 1920s, the parallel with the recent productivity slowdown should not be overstated. First, though productivity growth from electrification was sluggish during the early 1900s, the U.S. economy overall had a much higher level of output growth than the growth levels experienced over the past three decades. Data from table A-XVIII of John Kendrick (1961) imply that output growth between 1899 and 1909 in the U.S. economy was 4.2 percent a year, while between 1909 and 1919, it was 3 percent, and between 1920 and 1929, output grew by 3.6 percent a year. Second, as noted by Stephen Oliner and Daniel Sichel (1994), computers and other advanced office equipment have only been a trivial part of the aggregate capital stock of the U.S. economy until the mid-1990s. It is therefore unlikely that the whole of the U.S. economy has been adapting to the changes in this relatively small part of the capital stock. Finally, as shown by Ernie Brendt, Catherine Morrison, and Larry Rosenblum (1994), more computerized sectors did not perform any better in terms of labor productivity growth over this period; this pattern is also difficult to reconcile with a computer-led technological revolution.

It is also useful to note that although computers have no doubt increased our standards of living and quality of life over the past thirty years, they may be much less radical innovations than certain previous new technologies (see Gordon 1998). To gain perspective,

[29] Another argument that applies only against approaches based on the Nelson-Phelps hypothesis is that historical evidence is not necessarily in line with a view that demand for skills always increases during times of rapid technical change. As discussed in the introduction, the major technological changes of the early nineteenth century appear to have been largely skill-replacing (unskill-biased), even though they seem as radical as computer technology. This suggests that it is the skill bias of technology, not merely its rapid arrival, that is important for the demand for skills.

consider the difference that the telegraph made to a world in which the fastest medium of communication was pigeons. Mokyr (1990, p. 124) describes this as follows:

> The telegraph had an enormous impact on 19th-century society—possibly as great as that of the railroad. Its community and political value was vast, as was its effect in coordinating international financial and commodity markets. Unlike the railroad, it had no close substitutes, the closest being homing pigeons and semaphore.

Or consider the difference that the automobile and air conditioning made to the quality of life, and electricity and interchangeable parts made to the manufacturing sector. As also pointed out by Gordon (1998), compared to these improvements, the switch from mainframes to PCs, or from telephone to e-mail, or from the typewriter to the word processor may be modest.[30]

A final problem for all of the approaches based on exogenous technological developments is the coincidence in the timing of this change, and the rapid increase in the supply of skilled workers. Recall that there was a very large increase in the supply of college graduate workers during the late 1960s and the early 1970s (figure 1 and table 1 show the large increase in the employment share of college workers between 1970 and 1980). So the acceleration in skill bias is either concurrent with, or immediately follows, this large increase in the supply of skills. There is no a priori reason to expect the acceleration in skill bias to coincide with the rapid increase in the supply of skills. Those who want to subscribe to the exogenous technological progress view have to explain this as a chance event.[31]

5.2 *Endogenous Skill-Biased Technical Change*

The theories discussed so far presume technical change to be skill-biased *by nature* (or, at the very least, recent technologies to have increased the demand for skills due to exogenous reasons). A different perspective is to link the types of technologies that are developed and adopted to (profit) incentives, or to *demand pull* as emphasized by Schmookler (1966).[32]

Historical evidence is consistent with the notion that profit incentives and opportunities are important for the development and introduction of new

[30] Another argument is that our ability to measure TFP growth may have deteriorated following a change in technological regime. However, as Martin Bailey and Gordon (1988) document, productivity slowdown has been concurrent in many sectors, some of them with little problems in measuring output or output quality. It is interesting to note, however, that evidence in favor of this hypothesis may yet emerge, especially since productivity growth has been quite rapid during the past three years (but see Gordon 1998, and more recently, Dale Jorgensen and Kevin Stiroh 2000, on this).

[31] One could argue that the supply of skilled workers increased because, during the 1960s, workers anticipated that there was going to be a technological discontinuity in the decades to come, and responded to this by increasing their education. This story appears quite unreasonable, however. There is no evidence that anyone, let alone teenagers, foresaw the technological developments of the 1970s and the 1980s as early as the 1960s. Moreover, the increase in the supply of skills can be largely explained by two factors. First, the Vietnam era draft laws encouraged young males to stay in college longer (and indirectly also influenced female enrollments). Second, college enrollments were on an upward trend since the early 1950s, and much of the increase in the supply of college graduate workers is accounted for by the interaction of this upward trend with the very large relative size of the baby boom cohorts.

[32] This is also the approach taken by the endogenous growth theory, which determines the overall rate of technical change—but not the degree of skill bias—from profit incentives (e.g., Romer 1990; Gene Grossman and Elhanan Helpman 1991; Aghion and Howitt 1992). An advantage of the endogenous-technology perspective in this context is that it provides clear reasons for the degree of skill bias to increase even without a change in the overall pace of technological improvement —see below.

technologies. Fernand Braudel (1984, p. 566) took a strong position on this:

> [T]he efficient application of technology lags, by definition, behind the general movement of the economy; it has to be called on, sometimes several times, to meet a precise and persistent demand.

An interesting example of the timing of technological development responding to profit incentives is given by the introduction of the electric street car in U.S. cities during the late nineteenth century. In his history of electricity in the United States, David Nye (1990) describes this as follows:

> Cities grew larger, better transportation was needed, so the [electric] trolley was invented, called into being by the crowded late nineteenth century cities . . . . By the 1870s large cities had ceased to be accessible by foot, or built to the scale of pedestrians, and traffic congestion was terrible. (p. 85)

This created the profit opportunities to develop and introduce the electric trolley. The technological requirements had been met long before, and awaited these profit opportunities. Nye writes, "However great the need for the electric trolley after 1870, it was hardly a new idea; it had been the object of experiment during four decades" (p. 86).

Another example of the type of innovation responding to profit incentives is provided by the cotton gin. In the late eighteenth and early nineteenth centuries, only green seed cotton, which was difficult to clean, could be grown in most of the American South, and Britain imported most of its cotton from the West Indies, Brazil, and India. A machine to remove the seeds was essential for the success of American cotton. In contrast to almost all other textile innovations that were taking place in England and Europe, such a machine, the cotton gin, was developed in the United States in 1793 by Eli Whitney in response to this need. The impact of the cotton gin on the South was nothing short of spectacular. In the court case over the patent rights, Judge Johnson wrote:

> "[. . . as a result of the cotton gin] . . . individuals who were depressed with poverty, and sunk with idleness, have suddenly risen to wealth and respectability. Our debts have been paid off, our capital increased; and our lands are treble in value." (Quoted in Constance Green 1956, p. 92)

Within a short time, Eli Whitney's gin turned the United States from a cotton importer into the largest cotton exporter in the world.

Schmookler (1966) provides a famous argument for the importance of *demand pull* in the development of many technologies. He documents rapid innovations in railroads following increased purchases of railroad equipments, and more generally argues that industries with greater investments experience faster technological progress because the returns to such progress are greater. A natural next step is then to argue that the degree of skill bias in technical change is also determined by profit opportunities and by the demand for different types of technologies. Here, by endogenous (skill bias) technology approach I mean the view that the degree of skill bias in technical change is influenced by profit incentives.[33]

A key determinant of profitability is market size. As Schmookler (1966) stated in the title of two of his chapters: "*The amount of invention is governed by the extent of the market*." The most successful businessmen have always been aware of this. For example, Matthew

[33] An alternative explanation for the increase in wage inequality based on endogenous technical change is offered by Huw Lloyd-Ellis (1999). In his model, it is the interaction between endogenous technical change and the slowdown in the growth of labor quality that leads to increased inequality. Skill bias is not endogenous in Lloyd-Ellis' model.

Boulton wrote to his business partner, James Watt, "It is not worth my while to manufacture your engine for three countries only, but I find it very well worth my while to make it for all the world" (quoted in Michael Scherer 1984, p. 13). Schmookler (1966) similarly provided many examples where market size was crucial in determining the directions of technical change. The horseshoe is perhaps the most interesting one. Schmookler documented that there was a very high rate of innovation throughout the late nineteenth and early twentieth centuries in this very ancient technology, invented in the second century B.C., and no tendency for inventors to run out of additional improvements. On the contrary, inventions and patents increased because demand for horseshoes was high. Innovations came to an end only when "the steam traction engine and, later, internal combustion engine began to displace the horse . . ." (p. 93).

According to this reasoning, the development of skill-biased technologies will be more profitable when they have a larger market size—i.e., when there are more skilled workers. Therefore, the equilibrium degree of skill bias could be an increasing function of the relative supply of skilled workers. An increase in the supply of skills will then lead to skill-biased technical change. Furthermore, an acceleration in the supply of skills can lead to an acceleration in the demand for skills. It is useful to link this approach to technological development with the above framework. While the above supply-demand framework explains the prices of skills by supply and technology, the perspective of endogenous skill bias relates technology to the supply of skills.[34] Tinbergen, in his pioneering study of the supply-demand framework, in fact, foresaw this possibility, and wrote (1975, p. 61): ". . . an inequality-furthering phenomenon is technological development. But need it be? Increasingly we get the feeling that technological development is not simply something given, but that it may be guided, within limits."

At some level, the idea that there will be more technologies developed, created and adopted for skilled workers—"within limits"—when there are more skilled workers to use them is quite appealing. An extreme form of this view is captured by my model in Acemoglu (1998), where forward-looking profit-maximizing firms create new technologies anticipating the profitability of these different investments. According to this view, it would be the Vietnam War draft laws and the high college enrollment rates of the baby boom cohorts that *induced* the development of computers. Such an interpretation is not literal. A more plausible interpretation may be that new technological platforms—*macroinventions* to use Joel Mokyr's term, or *General Purpose Technologies* to use Bresnahan and Trajtenberg's term—stem from advances in basic science or from labs with little profit-maximizing incentive. The development of the microchip would be such a macroinvention. But what matters for most workers in the labor force is how this new technological platform is developed, i.e., the *microinventions* that follow the macroinvention. At the expense of oversimplifying, we can say that the microchip could have been used to develop advanced scanners to increase the productivity of unskilled workers, or advanced computer-assisted machines to be used by skilled workers to replace unskilled workers. The theory of endogenous skill bias requires that the extent of the advances in these two technologies

[34] Naturally, it is also possible to link the supply of skills to skill premia. See below for a discussion.

is affected by profit opportunities. When there are more college graduates, computers become relatively more profitable to develop than scanners, and this explains the acceleration in skill bias.[35]

The endogenous response of firms to the increase in supply will raise the demand for skills. In fact, supply may not simply create its own demand, but the response of firms could be so pronounced that demand could *overshoot* the supply. In this theory, therefore, the increased supply may be the cause of the increase in the skill premium (see Acemoglu 1998, and also Michael Kiley 1999). Here I outline a simplified version of this theory based on the above framework.

Suppose that consumers have a utility function defined over $Y = [Y_l^\rho + Y_h^\rho]^{1/\rho}$, and that $Y_h = N_h H$ and $Y_l = N_l L$ where N_h and N_l can be interpreted as the number of specialized machines used with skilled and unskilled workers, respectively. This is equivalent to the above setup with $A_h = N_h$ and $A_l = N_l$. An increase in N_h relative to N_l will correspond to skill-biased technical change as long as $\sigma = 1/(1-\rho) > 1$. From consumer maximization, the relative price of skill-intensive goods is

$$p \equiv \frac{p_h}{p_l} = \left[\frac{N_h H}{N_l L}\right]^{\rho - 1}, \tag{16}$$

where once again p_h denotes the price of good Y_h and p_l is the price of Y_l.

Suppose now that these specialized machines are created and sold by profit-maximizing monopolists. Creating a new machine costs B units of the final good Y, and the marginal cost of producing these machines, once created, is zero. The marginal willingness to pay for an additional machine in the two sectors is given by the derivatives of $p_h Y_h$ and $p_l Y_l$ with respect to N_h and N_l, i.e.,

$$p_h H \text{ and } p_l L. \tag{17}$$

I assume that the creator of each new machine obtains this "market" marginal willingness to pay (see Acemoglu 1998, for a more rigorous and detailed discussion). Equation (17) therefore highlights two effects that encourage the creation of new technologies.

1. The price effect: technologies producing more expensive goods will be improved faster. Since goods using the scarce factor will command a higher price (see equation 16), this effect implies that there will be more innovation directed at the scarce factor—i.e., directed at unskilled workers during the 1970s and the 1980s.
2. The market size effect: a larger clientele for a technology leads to more innovation. Since the clientele for a technology is the number of workers who use it, the market size effect encourages innovation for the more abundant factor, and encourages more technologies for skilled and highly educated workers during the 1970s and the 1980s.

The creation of new machines will stop when the marginal increase in profits is equal to the marginal cost of innovation in both sectors. This implies that in equilibrium

$$\frac{p_h H}{p_l L} = 1, \tag{18}$$

i.e., the price and market size effects have to be balanced in equilibrium. How can equation (18) be satisfied? Since H/L

[35] There is some evidence that the composition of R&D shifted toward more skill-biased technologies during the period of the rapid increase in the supply of college-educated workers. From the R&D expenditure data reported by the NSF, in 1960 company funded R&D for office computing was 3 percent of the total company funded R&D expenditure. This ratio had increased to 13 percent by 1987, suggesting that during this period of rapid increase in the supply of skills, there was significantly more R&D directed to one of the technologies most complementary to skills.

is fixed, equation (18) can only hold if the relative price of skill-intensive goods, $p = p_h/p_l$, adjusts. From equation (16), this can only happen if N_h/N_l changes. Therefore, in this economy, the skill bias of technology has to adjust in order to "*clear the technology market.*" Combining (16) and (18), we obtain equilibrium skill bias as

$$\frac{N_h}{N_l} = \frac{A_h}{A_l} = \left(\frac{H}{L}\right)^{\rho/(1-\rho)}. \tag{19}$$

This equation shows that when $\rho > 0$, i.e., when skilled and unskilled good are gross substitutes, the market size effect will dominate the price effect, and a greater relative supply of skilled workers will lead to more skill-biased technologies—higher N_h/N_l.

Finally, by substituting from equation (19), the skill premium in this economy is

$$\omega = \frac{p_h N_h}{p_l N_l} = \left(\frac{H}{L}\right)^{(2\rho-1)/(1-\rho)} = \left(\frac{H}{L}\right)^{\sigma-2}$$

where the final expression is obtained by combining (16) and (19).

The most important result is that if $\rho > 1/2$, i.e., if the elasticity of substitution σ is greater than 2, the skill premium will be an *increasing* function of the relative supply of skills.[36] This is because an increase in H/L encourages so much skill-biased technical change that the demand for skills increases more than enough to offset the increase in the supply of skills. As a result, the (long-run) relative demand for skills is an upward-sloping curve as drawn in figure 7, and an increase in the supply of skilled workers *increases* the skill premium.

[36] The result that the elasticity of substitution needs to be greater than 2 for the long-run relative demand to slope upwards is a feature of the simple model here, and does not generalize to richer environments. In any case, there are a number of estimates above 2, and a somewhat upward sloping relative demand curve for skills, even with this model's parameterization, is an empirical possibility.

There are a number of implications that follow from this approach. First, as the relative supply of skilled workers has been growing throughout the past sixty years, we expect technology to endogenously respond by becoming more skill-biased over time. If the elasticity of substitution between skilled and unskilled workers is greater than 2, i.e., $\rho > 1/2$, the increase in the demand for skilled workers would be more than enough to offset the increase in the supply of skilled workers, and the economy would be moving steadily along an upward-sloping relative demand curve for skills. This would explain why returns to college have been increasing over the past half century.

A new theory for the acceleration in skill bias also emerges from this simple model. According to this theory, the rapid increase in the supply of college educated workers during the 1970s created a more pronounced shift toward skill-biased technologies, further increased the demand for skill, and raised the college premium. This story becomes more interesting once we recognize that the equilibrium skill bias of technologies, N_h/N_l, is a sluggish variable determined by the slow buildup and development of new technologies. In this case, a rapid increase in the supply of skills first reduces the skill premium as the economy moves along a constant technology (constant N_h/N_l) curve as drawn in figure 7. After a while the technology starts adjusting, and the economy moves back to the upward-sloping relative demand curve, with a very sharp increase in the college premium. This theory therefore gives an interpretation for both the decline in the college premium during the 1970s and its subsequent surge, and relates both to the large increase in the supply of skilled workers.

For the key insights of this theory,

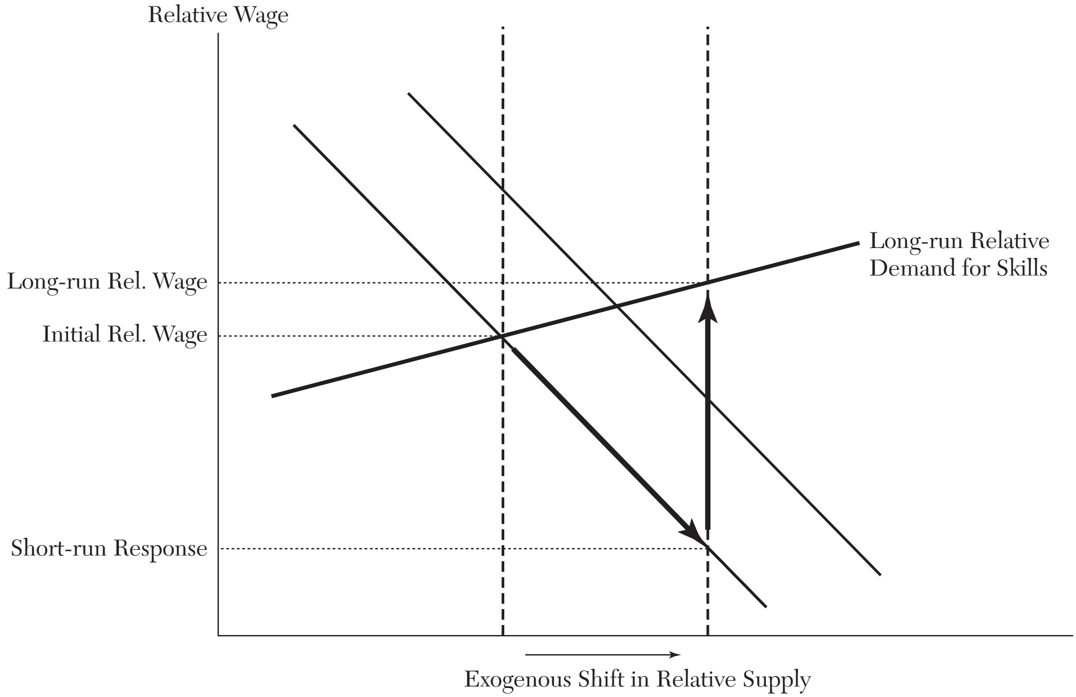

Figure 7. The Dynamics of the Relative Wage of Skilled Workers in Response to an Increase in the Supply of Skills with Endogenous Skill-Biased Technical Change

that increases in the relative supply of skills induce skill-biased technical change, we *do not need* the long-run relative demand curve to be upward-sloping. When $\rho < 1/2$, increases in the supply of skills still induce skill-biased change, but this technical change is not enough to prevent the skill premium from falling. Further "exogenous" skill-biased technical change is also necessary to explain why returns to schooling have risen over the past sixty years. With a downward-sloping long-run demand curve, the story for the 1970s and the 1980s is also different. The large increase in the supply of skills again moves the economy along a steeply downward-sloping constant technology demand curve. The response of technology then moves the economy to a less steep long-run demand curve as drawn in figure 8, raising the skill premium. Additional exogenous skill-biased technical change is then necessary for the skill premium to increase above its initial level.

There are also other historical episodes in which a large increase in the supply of skills appears to have affected the direction of technical change. High school enrollment and graduation rates doubled in the 1910s. Goldin and Katz (1995) argue that increased enrollments were mostly driven by supply side factors; changes in the location and curricula of schools and improvements in transportation technology. The skill premium fell sharply in the 1910s. But, despite the even faster increase in the supply of high school skills during the 1920s, the skill premium levelled off and started a mild increase. Goldin and Katz (1995) conclude that the demand for high school graduates must have

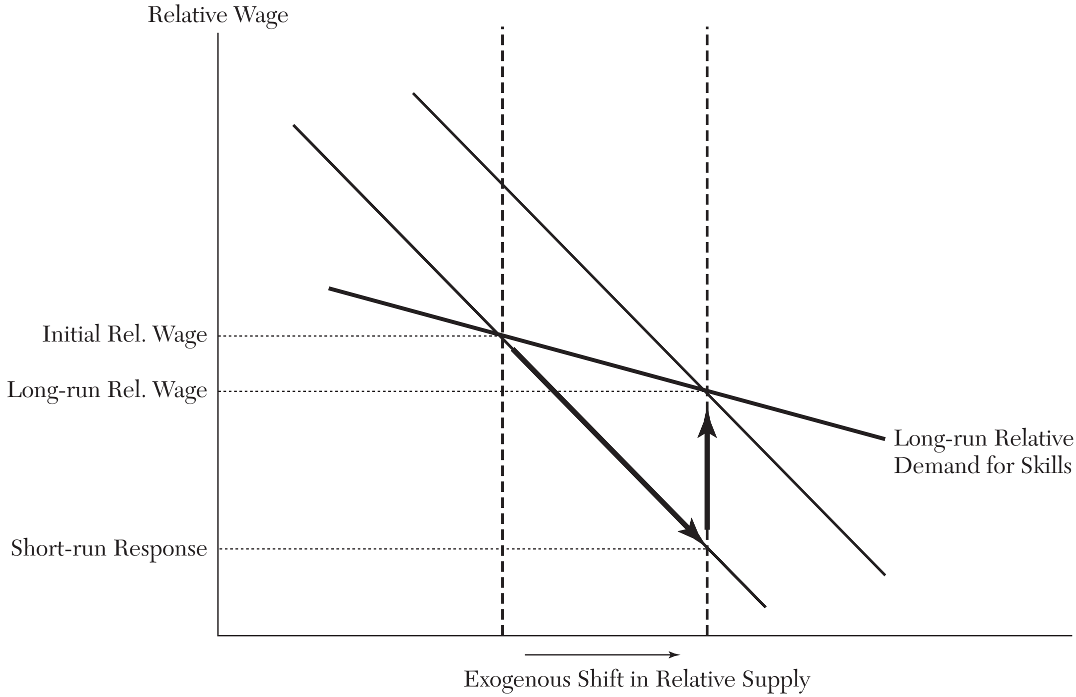

Figure 8. The Dynamics of the Relative Wage of Skilled Workers in Response to an Increase in the Supply of Skills with Limited Endogenous Skill-Biased Technical Change

expanded sharply starting in the 1920s, presumably due to changes in office technology and higher demand from new industries, such as electrical machinery, transport and chemicals (see also Goldin and Katz 1998).[37]

Another interesting case study comes from the response of the Israeli labor market to the influx of large numbers of highly educated immigrants from the former Soviet Union. The size of this influx was enormous: migration increased the Israeli population by 12 percent in the first half of the 1990s. A theory with exogenous technology would predict a large decline in the relative wages of educated workers, very much as in the case of Palestinian labor discussed above.[38] In practice, the education premium did not fall (e.g., Rachel Friedberg 1997). This seems to be mainly because most industries increased their employment of more skilled workers during this large influx (Neil Gandal, Gordon Hanson, and Matthew Slaughter 2000; and Sarit

[37] As Goldin and Katz (2000) show using data from Iowa Prairies, returns to education were most likely higher in 1915 than in 1950. Although this evidence suggests that the long-run relative demand curve for skills was downward sloping over this period, it is consistent with the notion of skill-biased technical change induced by an increase in the supply skilled workers. Specifically, during this period, demand for skills expanded very rapidly to accommodate the very large increase in the supply of high school graduates (see Goldin and Katz 1995, 2000).

[38] The key difference between the two episodes is that Palestinian labor is a relatively small fraction of the Israeli work force, so we expect much less of a technology response to changes in the educational composition of Palestinian labor. Furthermore, Palestinian college graduates are not a close substitute for Israeli college graduates, and only a limited range of occupations are open to them.

Cohen and Chang-Tai Hsieh 2000). This response suggests a change in the production structure toward more skilled workers, consistent with the theories outlined in this section.[39]

Despite this evidence showing simultaneous increases in the supply of, and demand for, skills in a number of episodes, it is difficult to distinguish exogenous and endogenous technical change. The exogenous technical change theory maintains that technical change is often skill-biased. Endogenous technical change theory instead suggests that new technologies should be skill-biased when the supply of skills increases. Since the supply of skills has increased most of the time over the past one hundred or so years, the implications of the two theories are quite similar. The increase in the supply of unskilled labor in the English cities during the early nineteenth century provides an interesting contrasting event for the two approaches. Bairoch (1988, p. 245) describes this rapid expansion as follows: ". . . between 1740 and 1840 the population of England . . . went up from 6 million to 15.7 million. . . . while the agricultural labor force represented 60–70% of the total work force in 1740, by 1840 it represented only 22%." Habakkuk (pp. 136–37) also emphasizes the increase in the supply of unskilled labor in English cities, and attributes it to five sources. First, enclosures released substantial labor from agriculture. Second, "population was increasing very rapidly" (p. 136). Third, labor reserves of rural industry came to the cities. Fourth, "there was a large influx of labor from Ireland" (p. 137). Finally, "technical changes in agriculture increased the supply of labor available to industry" (p. 137).

According to the endogenous technology hypothesis, this increase in the supply of unskilled labor should encourage unskill-biased technical change. And as predicted by this approach, there were major skill-replacing (unskill-biased) technologies introduced during this period, most notably the factory system replacing tasks previously performed by skilled artisans. Moreover, in his classic study, Habakkuk argues that the increase in the supply of labor was an important inducement to the development of factory methods. He also quotes an American historian, Handlin, to explain why the adoption of factory methods in the United States was somewhat delayed. Handlin wrote:

> [N]o matter what degree of standardization technical process of manufacturing reached, the absence of a cheap labor supply precluded conversion to factory methods. (p. 146)

Habakkuk placed much more importance on the role of wages in determining innovation decisions, a view that later became known as the "Habakkuk hypothesis." But he also emphasized the different availabilities of skilled labor in Britain and the United States. He wrote:

> [I]n both countries this provided manufacturers with an incentive to adopt and devise methods which replaced skilled by non-skilled . . . [but] . . . the English had a stronger incentive than the Americans to replace skilled by unskilled labor. (p. 152)

With a similar reasoning to Habakkuk and Schmookler, the endogenous technology view suggests that nineteenth-century businessmen took advantage of the rapid increase in the supply of labor

[39] Since Israel can be approximated by a small open economy, another possibility is a change in the output mix and trade patterns. Gandal, Hanson, and Slaughter (2000) and Cohen and Hsieh (2000) find no evidence for this, and show that demand for skills increased in all Israeli sectors. Cohen and Hsieh (2000) also argue that because many Russian immigrants initially worked in low-skill occupations, the supply of skills to the Israeli economy may not have increased by much.

in the cities by developing the factory system. According to this view, there is a close link between the skill-replacing technologies of the nineteenth century and the change in the factor supplies faced by employers—"the reserve army of unskilled labor." Although these historical examples are informative, they do not reveal whether endogenous technology choices are important in understanding more recent skill-biased technical change. A systematic study of how technologies respond to large changes in the relative supply of skills is clearly a worthwhile future research project.[40]

An important aspect of the endogenous technology theory is that it makes relatively tight predictions regarding the future path of technical change. While, with exogenous skill bias theories, there is no clear reason to expect a further acceleration or deceleration in the skill bias of new technologies, according to this endogenous skill bias theory, the future path of technical progress should be closely tied to the path of the supply of skills. If the relative supply of skills continues to increase, we should expect further skill-biased technical change.[41]

As discussed above, a major problem for the "technological revolution" models is the slowdown in TFP. Since the endogenous technology approach places the emphasis on which type of technologies are developed, it is not inconsistent with the slow growth in TFP during the past thirty years: an acceleration in the skill bias of new technologies does not require faster technical progress. The evidence presented in Richard Newell, Adam Jaffee, and Robert Stavins (1999) is consistent with the notion that changes in the direction of technical change can happen without an increase in the overall rate of productivity growth. They show that innovation in air conditioners responded to changes in energy prices by becoming more energy-efficient, but find no increase in the rate of productivity growth. In fact, Acemoglu (1998) and Kiley (1999) show that the increased effort of firms to develop more skill-biased technologies could run into decreasing returns, and hence may cause a slowdown in TFP growth. Intuitively, the overall productivity growth in the economy is maximized with a balanced distribution of resources toward developing skill-biased and unskill-biased technologies (due to decreasing returns to each activity). During periods of rapid skill-biased technical change, all resources go into developing skill-biased machines, and cause a decline in advances in unskill-biased technologies. Because of the decreasing returns to

[40] It is also useful to note that the skill bias of technology most likely responds not only to changes in the relative supply of skills, but to a variety of other factors. Recent work by Marcus Mobius (2000) and David Thesmar and Mathias Thoenig (2000) shows how the size of the product market, the degree of competitive pressure and instability facing firms may affect the way firms choose to organize, and therefore the demand for skills. Moreover, Mobius suggests that these changes reduced the demand for skills during the nineteenth century as there was greater standardization of products, but increased this demand during the past several decades as the need for flexibility increased. How the organization of product markets and the extent of competition affect technology choices and the demand for skills is a very promising area for future research.

[41] Although evidence from the 1990s suggests that skill-biased technical change is now slower, there is not yet sufficient evidence to decide whether the rapid skill-biased technical change of the 1980s has come to an end. It also has to be noted that the increase in the relative supply of college educated workers in the 1990s may have been less than the previous trend (see figure 1), and this may have affected the technology choices of firms. In particular, with the increased labor force participation of less skilled workers, there may now be a sufficient number of unskilled workers supplying labor at low wages to make the further development of unskilled-labor-complementary technologies quite profitable.

scale, improvements in the other sector will not fully offset this decline, and overall TFP growth will fall.[42]

Finally, it is useful to discuss briefly the response of skills to technology. The analysis so far treated the supply of skills as exogenous, and investigated the implications of the supply on the demand for skills. Naturally, the supply of skills will also respond to economic incentives: more workers are likely to acquire skills when skill premia are higher. Such supply choices can be easily incorporated into this framework. Suppose, for example, that the relative supply of skills, H/L, is an increasing function of the skill premium, ω. In this case, if the long-run demand curve for skills is upward-sloping, we can have an equilibrium path in which both the relative supply of skills and the skill premium increase together over time (see Acemoglu 1998). This equilibrium configuration gives us an attractive interpretation for the joint behavior of college skills and the college premium in the U.S. economy over the past sixty years (see figure 1): high returns to schooling encourage education, which in turn induce more skill-biased technical change, increasing returns to schooling again.

5.3 *A Puzzle: The Decline in Wages of Low-Skill Workers*

A common shortcoming of all the pure technology approaches discussed in this section is that they do not naturally predict stagnant average wages and/or falling wages for unskilled workers.[43] In the basic framework of section 3, average wages always increase when the supply of educated workers increases, and all wages should rise in response to an increase in the productivity of skilled workers, A_h. Yet, over the past thirty years the wages of low-skill workers have fallen in real value, which contrasts with their steady increase in the previous thirty years.

Models of faster technological progress would naturally predict that unskilled workers should benefit from this faster progress. The endogenous technology approach discussed in the previous subsection, on the other hand, predicts that there may be no improvements in the technologies for unskilled workers for an extended period of time because skill-biased innovations are more profitable than unskill-biased innovations. Yet in that case, their wages should be stagnant or increase slowly, but *not fall*.

Some of the studies mentioned above have suggested explanations for the fall in the wages of low-skill workers. For example, recall that Galor and Moav (2000) argue that faster technological change creates an "erosion effect," reducing the productivity of unskilled workers. Using equation (3) from above, in the simplified version of their model discussed in section 5.1, the unskilled wage is $w_L = \phi_l(g)a[1 + \phi_h^{\rho}(H/L)^{\rho}]^{(1-\rho)/\rho}$, where the ϕ_l function captures the erosion effect. The rate of growth of unskilled wages will be $\dot{w}_L/w_L = g(1 + \varepsilon_\phi)$, where ε_ϕ is the elasticity of the ϕ_l function which is negative by the assumption that $\phi'_l < 0$. If this elasticity is less than -1, an acceleration in economic growth can reduce the wages of

[42] The view that too much effort toward improving the skill-biased technologies may be related to the TFP slowdown is consistent with the pattern of sectoral TFP growth observed recently. As Gordon (1998) and Jorgensen and Stiroh (2000) document, there has been rapid TFP growth in computer-producing sectors, but mediocre, or even disappointing, TFP growth in other sectors.

[43] However, recall that if the increase in nonwage benefits is taken into account, average wages increased over this period. So the more robust fact might be the fall in the real wages of low-skill workers.

low-skill workers due to a powerful erosion effect.

Acemoglu (1999a) and Caselli (1999) derive a fall in the wages of less-skilled workers because the capital-labor ratio for low-education/low-skill workers falls as firms respond to technological developments. In Caselli's model this happens because the equilibrium rate of return to capital increases, and in my paper, this happens because firms devote more of their resources to opening specialized jobs for skilled workers.

Consider the following simple example to illustrate this point. There is a scarce supply of an input K, which could be capital, entrepreneurial talent or another factor of production. Skilled workers work with the production function

$$Y_h = A_h^{\alpha} K_h^{1-\alpha} H^{\alpha}, \tag{20}$$

while unskilled workers work with the production function

$$Y_l = A_l^{\alpha} K_l^{1-\alpha} L^{\alpha}, \tag{21}$$

where K_l and K_h sum to the total supply of K, which is assumed fixed. For simplicity, assume that Y_l and Y_h are perfect substitutes. In equilibrium, the marginal product of capital in the two sectors has to be equalized, hence

$$\frac{K_l}{A_l L} = \frac{K - K_l}{A_h H}.$$

Therefore, an increase in A_h relative to A_l will reduce K_l, as this scarce factor gets reallocated from unskilled to skilled workers. The wages of unskilled workers, $w_L = (1-\alpha)A_l^{\alpha} K_l^{1-\alpha} L^{\alpha-1}$, will fall as a result.

An innovative version of this story is developed by Paul Beaudry and David Green (2000). Suppose that equation (21) above is replaced by $Y_l = A_l^{\eta} K_l^{1-\eta} L^{\eta}$, with $\eta < \alpha$, and K is interpreted as physical capital. This implies that unskilled workers are more "dependent" on capital than skilled workers. Beaudry and Green show that an increase in H/L can raise inequality, and depress the wages of low-skill workers. Although this is related to the effects of the increase in the relative supply of skills on the path of technological progress discussed in the last subsection, the mechanism in Beaudry and Green's paper is quite different. The increase in H/L increases the demand for capital, and pushes the interest rate up. This increase in the interest rate hurts unskilled workers more than skilled workers because of the assumption that $\eta < \alpha$.

A potential problem with both the Beaudry and Green and Caselli stories is that they explicitly rely on an increase in the price of capital. Although the interest rates were higher during the 1980s in the U.S. economy, this seems mostly due to contractionary monetary policy, and related only tangentially to inequality. Perhaps future research will show a major role for the increase in the interest rates in causing the decline in the wages of low-education workers, but as yet, there is no strong evidence in favor of this effect.[44]

Overall, a potential problem for models based on technical change is to account for the decline in the wages of low-skill workers.[45] I argue in the next section that the effect of technical change on the organization of the labor

[44] Acemoglu (1999a), which is more in the spirit of the organizational theories discussed below, obtains the decline in the wages of unskilled workers through a change in the organization of production, which also entails a reallocation of capital away from them, but no increase in the rate of return to capital.

[45] Another possibility is that some of the technological developments of the past two decades have been "truly labor-replacing," for example, corresponding to an increase in $B_l(t)$ or b_t in terms of the production function in footnote 13. Autor, Levy, and Murnane (2000), for example, suggest that computers have replaced unskilled routine tasks. This possibility has not been extensively researched yet.

market both amplifies the effect of technology on wage inequality, and provides a possible explanation for this decline.

6. *Ramifications of Technical Change*

This section discusses how technical change can affect labor market prices by transforming the organization of the labor market. The idea that technology affects the organization of production, and the institutions around it, is an old one. Marx put it in a dramatic fashion: "The hand-mill gives you society with the feudal lords; the steam-mill, society with the industrial capitalist." The argument here is not as extreme, but related: recent technological developments may have led to important changes in the organization of production.

My focus here is on three sets of changes that could account for the fall in the wages of low-skill workers: the transformation of the organization of firms; change in labor market "institutions,"[46] particularly the decline in unionization; and the interaction between international trade and technical change. Organizational change often destroys the types of jobs that pay high wages to low-skill workers. Deunionization reduces the bargaining power of low-skill workers. And international trade with less developed countries (LDCs) increases the effective supply of unskilled labor and depresses the marginal value product of less skilled workers in the U.S. economy. Therefore, all three changes could be responsible for the changes in the U.S. wage structure and for the decline in the wages of low-skill workers. Nevertheless, I argue that these factors by themselves are not the major cause of the increase in inequality. Instead they have become powerful actors only by interacting with technical change, amplified the direct effect of technical change on inequality, and contributed to the fall in the wages of low-skill workers.

[46] I am using the term institutions loosely here, to capture the rules of the game in the labor market, patterns of bargaining, as well as government labor market policy.

6.1 *Organizational Change and Inequality*

A variety of evidence suggests that important changes in the structure of firms have been taking place in the U.S. economy over the past 25 years. Moreover, it seems clear that a major driving force for this transformation is changes in technologies (hence the view that technical change is essential for the changes in the organization of firms). For example, team production and other high-performance production methods are now widespread in the U.S. economy (e.g., Casey Ichniowski, Giovanna Prennushi, and Kathryn Shaw 1997, or Eileen Applebaum and Rosemary Batt 1994). Similarly, Peter Cappelli and Steffanie Wilk (1997) show that there has been an increase in the screening of production workers, especially from establishments that use computer technology and pay high wages.

Murnane and Levy (1996) report case study evidence consistent with this view. From their interviews with human resource personnel at a number of companies, they describe the change in the hiring practices of U.S. companies. A manager at Ford Motor company in 1967 describes their hiring strategy as follows: "If we had a vacancy, we would look outside in the plant waiting room to see if there were any warm bodies standing there. If someone was there and they looked physically OK and weren't an obvious alcoholic, they were hired" (p. 19). In contrast, comparable companies in the late 1980s use a very

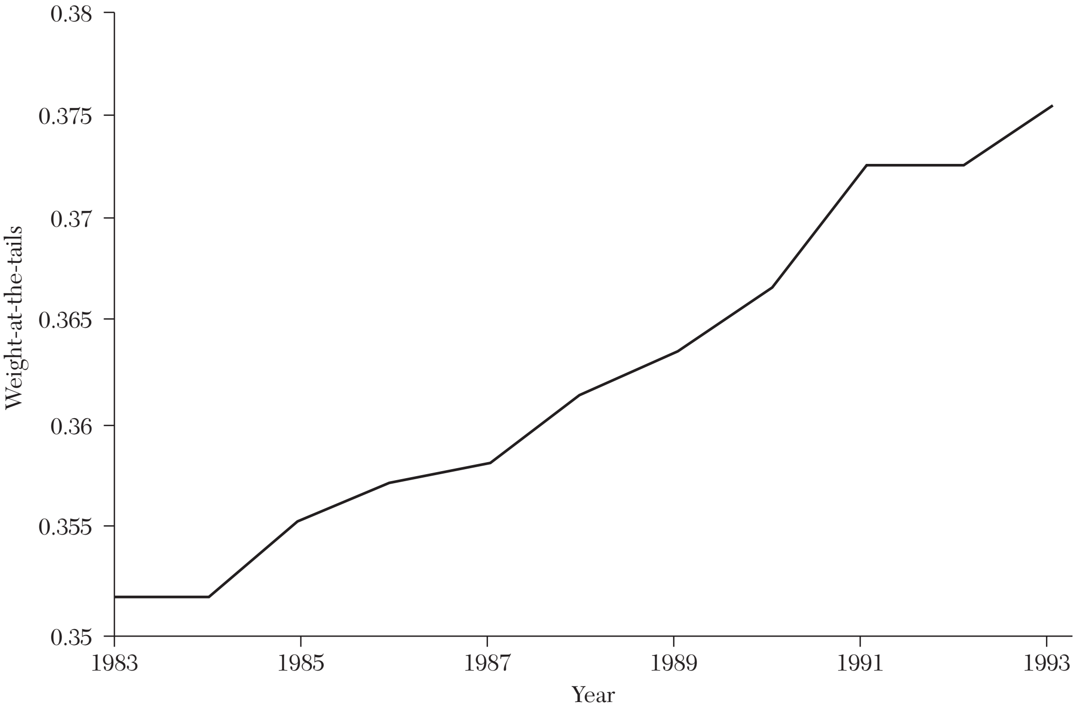

Figure 9. The Evolution of the Percentage of Employment in the Top and Bottom 25 Percentile Industry-Occupation Cells (weight-at-the-tails of the job quality distribution)

different recruitment strategy. Murnane and Levy discuss the cases of Honda of America, Diamond Star Motors, and Northwestern Mutual Life. All three companies spend substantial resources on recruitment and hire only a fraction of those who apply. Kremer and Maskin (1999) provide evidence of more segregation of workers across establishments. It seems that high-wage workers are now much more concentrated in certain establishments. Similarly, in Acemoglu (1999a) I documented a change in the composition of jobs over the past twenty years. Figure 9 here replicates a pattern found in that paper, and plots the total percentage of workers employed in the top 25-percent and bottom 25-percent industry-occupation cells (what I called weight-at-the-tails of the job quality distribution). These are the cells (job types) that pay relatively high or relatively low wages. In 1983, 35 percent of employment was in the top and bottom 25-percent job categories. By 1993, this number had risen to just under 38 percent. So, approximately 2.5 percent more workers now have either higher or lower quality jobs rather than medium quality jobs. The actual changes in the distribution of jobs may be much larger than this, since substantial changes in the types of jobs often take place within given occupations.

The view that changes in the organization of firms have had a fundamental effect on the labor market is often expressed in the popular press, and in the organizational literature (e.g., Shohana Zuboff 1988). This organizational approach is formalized by Kremer and Maskin (1999), Acemoglu (1999a), Mobius (2000), Thesmar and Thoenig (2000), and Gilles Duranton (2001). Kremer and Maskin consider a production function which distinguishes between managers and workers. They show that a change in technology or an increase in the dispersion of skills may encourage high-skill workers to match with other high-skill workers, rather than work as managers in establishments employing low-skill workers.

Here I outline a simple model, synthesizing Kremer and Maskin (1999) and Acemoglu (1999a), that captures the effect of the technical change on the organization of production, and via this channel, on wage inequality. The basic idea is simple. As the productivity of skilled workers increases, it becomes more profitable for them to work by themselves in separate organizations rather than in the same workplace as the unskilled workers. This is because when the skilled and the unskilled work together, their productivities interact, and unskilled workers may put downward pressure on the productivity of skilled workers (for example, because unskilled workers have to implement part of the production process designed by skilled workers).

Specifically, suppose that firms have access to the following production functions

the old-style production function:

$$Y = B_p[(A_l L)^\rho + (A_h h_O)^\rho]^{1/\rho},$$

the new-organization production function:

$$Y = B_s A_h^\beta h_N,$$

where h_O is the number of skilled workers employed in the old-style firms, and h_N is the number of skilled workers employed in new organizations separately from unskilled workers. The fact that when they are employed in the same firm these two types of workers affect each other's productivity is captured by the CES production function. This formulation implies that if the productivity (ability) of unskilled workers, A_l, is very low relative to A_h, they pull down the productivity of skilled workers. In contrast, when they work in separate firms, skilled workers are *unaffected* by the productivity of unskilled workers. Moreover, $\beta > 1$, which implies that improvements in the productivity of skilled workers has more effect on the productivity of new-style organizations. The parameters B_p and B_s capture the relative efficiency of old and new-style production functions.

The labor market is competitive, so the equilibrium organization of production will maximize total output, given by $B_p[(A_l L)^\rho + (A_h h_O)^\rho]^{1/\rho} + B_s A_h^\beta (H - h_O)$, where $h_O \in [0, H]$ is the number of skilled workers employed in the old-style organizations. For all cases in which $h_O > 0$, the solution to this problem will involve

$$\begin{aligned} w_H &= B_p A_h^\rho h_O^{\rho-1}[A_l^\rho L^\rho + A_h^\rho h_O^\rho]^{(1-\rho)/\rho} \\ &= B_s A_h^\beta, \end{aligned} \tag{22}$$

i.e., skilled workers need to be paid $B_s A_h^\beta$ to be convinced to work in the same firms as the unskilled workers. The unskilled wage is

$$\begin{aligned} w_L &= B_p A_l^\rho L^{\rho-1}[A_l^\rho L^\rho + A_h^\rho h_O^\rho]^{(1-\rho)/\rho} \\ &< w_H. \end{aligned} \tag{23}$$

Now consider an increase in A_h. Differentiating (22) yields $\partial h_O/\partial A_h < 0$, that is, there will be fewer skilled workers working with the unskilled. Moreover, differentiation also gives $\partial(A_h h_O)/\partial A_h < 0$, so the efficiency units of skilled workers that the unskilled work with declines. From (23), this implies that $dw_L/dA_h < 0$. Therefore, skill-biased technical change encourages skilled workers to work by themselves, and as a result, unskilled wages fall. Intuitively, because, in the old-style organizations, the productivity of skilled workers depends on the ability of unskilled workers, when the skilled become even more productive, the downward pull exerted on their productivity by the unskilled workers becomes more costly, and they prefer to work in separate organizations. This reduces the ratio $A_h h_O / L$ and depresses unskilled wages. As a result, improvements in technology, which normally benefit unskilled workers as in section 3, may hurt unskilled workers because they transform the organization of production.

An increase in B_s/B_p, which raises the relative profitability of the new organizational form, also leads to further segregation of skilled and unskilled workers in different organizations. This last comparative static result is useful since Bresnahan (1999) and Autor, Levy and Murnane (2000) argue that by replacing workers in the performance of routine tasks, computers enabled a radical change in the organization of production.[47] This is reminiscent of a technological change that makes the new-organization production function more profitable.

These organizational stories are attractive since they provide a unified explanation for the changes in the wage structure and the apparent changes in the organization of firms. An interesting recent paper by Eve Caroli and Van Reenan (1999) provides evidence suggesting that changes in wages have been accompanied by changes in organizational forms. Acemoglu (1999a) and Kremer and Maskin (1999) also provide evidence suggesting a number of organizational changes in the U.S. economy during the past 25 years. Nevertheless, this evidence does not yet enable an assessment of whether changes in organizational forms have been an important contributor to the changes in labor market prices, and future research is required to determine the role of organizational change in the rise in inequality.

6.2 *Institutional Change*

Labor market "institutions," including minimum wage laws, the importance of collective bargaining in wage determination, and perhaps social norms, undoubtedly have an important effect on the distribution of wages. The Great Compression in the wage distribution after the Second World War is difficult to explain without invoking changes institutions and social norms (see, e.g., Goldin and Robert Margo 1992). Could changes in labor market institutions also account for the increase in wage inequality and the discontinuity in that demand for skills during the past decades?

Two major changes in labor market institutions over the past 25 years are the decline in the real value of state and federal minimum wages and the reduced importance of trade unions in wage determination. Although many economists suspect that these institutional changes may be responsible for the changes in the structure of the U.S. labor market (see Freeman 1991; DiNardo, Fortin, and Lemieux 1995; Lee 1999), I will argue that these changes are unlikely to be the major cause of the recent increase in U.S. wage inequality.

The real value of the minimum wage was eroded throughout the 1980s as the nominal minimum wage remained constant for much of this period. Since the minimum wage is likely to increase the wages of low-paid workers, this decline may be responsible for increased wage dispersion. DiNardo et al. (1995) and

[47] A related perspective is offered by Aghion (2001), who also argues that computers replace unskilled tasks. He suggests that computers are a "general-purpose technology," so their diffusion follows an inverted S shaped pattern. He suggests that as more and more firms adopted computers over the past decades, demand for unskilled workers fell rapidly.

Lee (1999) provide evidence in support of this hypothesis. Although the contribution of the decline in the minimum wage to increased wage dispersion cannot be denied, most economists believe that this is unlikely to have been a major factor in the changes in the U.S. wage structure. First, only a small fraction of male workers are directly affected by the minimum wage (even in 1992, after the minimum wage hike of 1990–91, only 8 percent of all workers between the ages of 18 and 65 were paid at or below the minimum wage). Although the minimum wage may increase the earnings of some workers who are not directly affected, it is unlikely to affect the wages above the median of the wage distribution. But as figure 3 shows, the difference between the 90th percentile and the median behaves very similarly to the difference between the median and the 10th percentile.[48] This implies that whatever factors were causing increased wage dispersion at the top of the distribution are likely to have been the major cause of the increase in wage dispersion throughout the distribution. Second, the erosion in the real value of the minimum wage started in the 1980s, whereas, as shown above, the explosion in overall wage inequality began in the early 1970s (subject to the caveat raised in footnote 11).

The declining importance of unions may be another important factor in the increase in wage inequality. Unions often compress the structure of wages and reduce skill premia (see for example Lloyd Reynolds 1951; or Freeman and James Medoff 1984). Throughout the postwar period in the U.S. economy, unions negotiated the wages for many occupations, even indirectly influenced managerial salaries (see DiNardo, Kevin Hallock, and Pischke 2000). Unions also explicitly tried to compress wage differentials. This suggests that the decline of unions may have been a major cause of the changes in the structure of wages.

Although deunionization could in principle be an important factor in the structure of wages, the extent and timing of deunionization suggests that it is not the major driving force of the increase in inequality. First, wage inequality increased in many occupations in which prices were never affected by unions (such as lawyers and doctors). Moreover, in the United States, deunionization started in the 1950s, a period of stable wage inequality. During the 1970s, though unionization fell in the private sector, overall unionization rates did not decline much because of increased unionization in the public sector. Overall union density was approximately constant, around 30 percent of the work force, between 1960 and 1975. It was the anti-union atmosphere of the 1980s and perhaps the defeat of the air-traffic controllers' strike that led to the largest declines in unionization, dating much of deunionization after the rapid increase in inequality during the early 1970s.[49] Evidence from other countries also paints a similar picture. For example, in the United Kingdom, wage inequality started its sharp increase in the

[48] Except during the early 1980s when there is a more rapid increase in inequality at the bottom of the wage distribution, most likely due to the falling real value of the minimum wage. There are substantially larger increases in inequality at the bottom of the distribution among female workers or in a sample that combines male and female workers. This reflects the larger effect of minimum wage laws on female earnings. Figure 3 shows that there are factors, other than the decline in the real value of the minimum wage, having a major effect on the top and the bottom of the male wage distribution.

[49] An interesting recent paper by Henry Farber and Bruce Western (2000) dates the major decline in union activity to the early 1980s, a few months before the air-traffic controllers' strike.

mid-1970s, while union density increased until 1980 and started a rapid decline only during the 1980s (Amanda Gosling 1998). In Canada, while unionization rates increased from around 30 percent in the 1960s to over 36 percent in the late 1980s (Riddell 1993, table 4.1), wage inequality also increased (see for example Freeman and Karen Needels 1993, figure 2.4).

Although the timing of deunionization does not appear to be consistent with this institutional change being the major cause of the changes in wage inequality, deunionization could clearly affect the wages of unskilled workers. One possibility is that deunionization is a contributing factor. But in this case, why did the unions decline while technology was rapidly becoming more skill-biased? Acemoglu, Aghion, and Violante (2001) suggest that deunionization may have been caused by the technological developments of the past decades. According to this perspective, technical change is the driving force of the changes in the wage structure, but it also leads to deunionization, and the resulting deunionization can have a significant indirect effect on wage inequality, causing the wages of less-skilled workers to fall.

To see the basic argument, suppose that production can be carried out either in unionized or nonunionized firms. In nonunionized firms, workers receive their marginal products, which I denote by A_h and A_l for skilled and unskilled workers. Assume that unions always compress the structure of wages—i.e., they reduce wage differentials between skilled and unskilled workers. This wage compression could be driven by a variety of factors. Acemoglu and Pischke (1999), for example, argue that unions encourage productive training, and such training is incentive compatible for firms only when the wage structure is compressed. Alternatively, collective decision making within a union may reflect the preferences of its median voter, and if this median voter is an unskilled worker, he will try to increase unskilled wages at the expense of skilled wages. It is also possible that union members choose to compress wages because of ideological reasons or for social cohesion purposes. The empirical literature supports the notion that unions compress wages, though it does not distinguish among the various reasons (see Freeman and James Medoff 1984). I capture wage compression in a reduced form way with the equation

$$\omega = \frac{w_H}{w_L} \leq \psi \frac{A_h}{A_l}, \tag{24}$$

where $\psi < 1$. Unions could never attract skilled workers unless they provided some benefits to them to compensate for the wage compression. Here I simply assume that they provide a benefit β to all workers, for example, because unions increase productivity (e.g., Freeman and Medoff 1984; and Freeman and Edward Lazear 1995), or because they encourage training. Alternatively, β could be part of the rents captured by the union. The zero-profit constraint for firms would be: $(w_H - \beta)H + (w_L - \beta)L \leq A_h H + A_l L$ (in the case where β stands for rents, the zero-profit condition ensures that the firm does not wish to open a non-union plant). Combining this equation with (24), and assuming that both hold as equality, we obtain

$$w_H = \frac{(A_h + \beta)H + (A_l + \beta)L}{A_h H + \psi^{-1} A_l L} A_h. \tag{25}$$

Skilled workers will be happy to be part of a union as long as w_H given by (25) is greater than A_h. As A_h/A_l increases—i.e., as skill-biased technical change raises the productivity of skilled workers relative to the unskilled—w_H will fall relative to A_h. Therefore, skill-biased technical change makes wage compression more costly for skilled workers, eventually destroying the coalition between skilled and unskilled workers that maintains unions.

The important point is that deunionization causes a decline in the wages of unskilled workers from $w_L = \frac{(A_h + \beta)H + (A_l + \beta)L}{A_h H + \psi^{-1} A_l L} \psi A_l$ to A_l. Unskilled workers, who were previously benefiting from wage compression imposed by unions, now experience a fall in real earnings. Therefore, technical change not only affects wage inequality directly, but also induces a change in labor market institutions. The effect of this change in institutions on inequality can be potentially larger than the direct effect of technical change, and explain the decline in the real wages of less-skilled workers.

Although Acemoglu, Aghion, and Violante (2001) provide some evidence consistent with these patterns, whether deunionization was important in the decline of the wages of low-skill workers and whether technical change is responsible for deunionization are open questions. It might also be interesting to investigate whether changes in technology may have also affected the coalition supporting the minimum wage, and hence played a role in the decline in the minimum wage during the 1980s. For example if unions, which have traditionally supported minimum wages, were weakened by the technological developments of that decade as argued in this subsection, technical change may have indirectly contributed to the weakening of the coalition in support of the minimum wage.[50]

6.3 *Trade, Technical Change, and Inequality*

Finally, I discuss another major change affecting the U.S. economy: the increased volume of international trade. I argue that increased international trade by itself is not the cause of the changes in the U.S. wage structure, but trade may have been an important factor in the rise of wage inequality by affecting the degree of skill bias of technical change. This subsection is somewhat different from the previous two, since it is not about the effect of technology on the organization of the labor market, but on the effect of a major change in regulations on technological developments.

Standard trade theory predicts that increased international trade with less-developed countries (LDCs), which are more abundant in unskilled workers, should increase the demand for skills in the U.S. labor market. So the increase in international trade may have been an underlying cause of the changes in U.S. wage inequality.

To discuss these issues, consider the two-good interpretation of the model in section 3. Consumer utility is defined over $[Y_l^\rho + Y_h^\rho]^{1/\rho}$, with the production functions for two goods being $Y_h = A_h H$ and $Y_l = A_l L$. Both goods are now tradable. For simplicity, let me just compare the U.S. labor market equilibrium without any trade (as characterized in section 3) to the equilibrium with full international trade without any trading costs.

Before trade, the U.S. relative price of skill-intensive goods, p_h/p_l, is given by

$$p^{US} = \frac{p_h}{p_l} = \left[\frac{A_h H}{A_l L}\right]^{\rho - 1}, \qquad (26)$$

[50] Finally, both the decline in the role that unions play and in the value of the minimum wage may have been caused by changes in certain social norms, for example, the norm of "equal work equal pay." The decline of the same norms could also be responsible for the increase in inequality (e.g., the emergence of the winner-take-all society as claimed by Robert Frank and Philip Cook 1996). Unfortunately, there is currently little research on the effect of social norms on inequality and on why inequality norms may have changed over the past thirty years.

where H and L denote the supplies of skilled and unskilled labor in the United States. The skill premium is then simply equal to the ratio of the marginal value products of the two types of workers, that is, $\omega^{US} = p^{US} A_h / A_l$. Next, suppose that the United States starts trading with a set of LDCs that have access to the same technology as given by A_h and A_l, but are relatively scarce in skills. Denote the total supplies of skilled and unskilled workers in the LDCs by $\hat{H}$ and $\hat{L}$ where $\hat{H}/\hat{L} < H/L$, which simply reiterates that the United States is more abundant in skilled workers than the LDCs.

After full trade opening, the product markets in the United States and the LDCs are joined, so there will be a unique world relative price. Since the supplies of skill- and unskill-intensive goods are $A_h(H + \hat{H})$ and $A_l(L + \hat{L})$, the relative price of the skill-intensive good will be

$$p^W = \left[\frac{A_h(H + \hat{H})}{A_l(L + \hat{L})}\right]^{\rho - 1} < p^{US}. \qquad (27)$$

The fact that $p^W > p^{US}$ follows immediately from $\hat{H}/\hat{L} < H/L$. Intuitively, once the United States starts trading with skill-scarce LDCs, demand for skill-intensive goods increases and pushes the prices of these goods up.

Labor demand in this economy is derived from product demands. The skill premium therefore follows the relative price of skill-intensive goods. After trade opening, the U.S. skill premium increases to

$$\omega^W = p^W \frac{A_h}{A_l} > \omega^{US} \qquad (28)$$

where the fact that $\omega^W > \omega^{US}$ is an immediate consequence of $p^W > p^{US}$. Therefore, trade with less developed countries increases wage inequality in the United States.

The skill premium in the LDCs will also be equal to ω^W after trade opening since the producers face the same relative price of skill-intensive goods, and have access to the same technologies. Before trade, however, the skill premium in the LDCs was $\hat{\omega} = \hat{p} A_h / A_l$, where $\hat{p} = (A_h \hat{H} / A_l \hat{L})^{\rho - 1}$ is the relative price of skill-intensive goods in the LDCs before trade. The same argument as above implies that $\hat{p} > p^W$, i.e., trade with the skill-abundant United States reduces the relative price of skill-intensive goods in the LDCs. This implies that $\omega^W < \hat{\omega}$; after trade wage inequality should fall in the LDCs.

Although in theory increased trade with the LDCs can be the cause of the rapid increase in the demand for skills, most evidence suggests that the direct effect of increased international trade on the U.S. labor market has been relatively minor. First, as equation (27) shows, the effect of international trade works through a *unique intervening mechanism*: more trade with the LDCs increases the relative price of skill-intensive goods, p, and affects the skill premium via this channel. In fact, in this simple framework, the percentage increase in the skill premium is proportional to the percentage increase in the relative price of skill-intensive goods. Perhaps the most damaging piece of evidence for the trade hypothesis is that most studies suggest the relative price of skill-intensive goods did not increase over the period of increasing inequality. Robert Lawrence and Slaughter (1993) found that during the 1980s the relative price of skill-intensive goods actually fell. Jeffrey Sachs and Howard Shatz (1994) found no major change or a slight decline. A more recent paper by Krueger (1997) criticized the methods and data used by these studies, and found an increase in the relative price of skill-intensive goods. Nevertheless, the increase in these prices is relatively small, so would not be able to account for the large increase in the skill premium experienced in the U.S. economy.

Second, with trade as the driving force, increased production of skill-intensive goods should be drawing workers away from other sectors. In contrast, as documented by Murphy and Welch (1993), Berman, Bound, and Griliches (1994) and Autor, Katz, and Krueger (1998), all sectors, even those producing less-skilled goods, increased their demands for more-educated workers. This pattern is not consistent with trade being the main driving force of the increase in the demand for skilled workers (though one has to bear in mind the increase in outsourcing in interpreting this fact; see Robert Feenstra and Hanson 1999).

Third, a direct implication of the trade view is that, as shown above, while demand for skills and inequality increased in the United States, the converse should have happened in the LDCs that have started trading with the more skill-abundant U.S. economy. The evidence, however, suggests that more of the LDCs experienced rising inequality after opening to international trade (see Hanson and Ann Harrison 1994; or Donald Robbins 1995). Although the increase in inequality in a number of cases may have been due to concurrent political and economic reforms, the preponderance of evidence is not favorable to this basic implication of the trade hypothesis.

Finally, a number of economists have pointed out that U.S. trade with the LDCs is not important enough to have a major impact on the U.S. product market prices and consequently on wages. Paul Krugman (1995) illustrates this point by undertaking a calibration of a simple North-South model. Katz and Murphy (1992), Berman, Bound, and Griliches (1994) and George Borjas, Freeman, and Katz (1997) emphasize the same point by showing that the content of unskilled labor embedded in the U.S. imports is small relative to the changes in the supply of skills taking place during this period.[51]

Although the above arguments suggest that increased international trade with the LDCs is not the major cause of the changes in the wage structure by itself, they do not rule out a powerful effect of international trade when it interacts with technical change. In a world with endogenous technical change, increased international trade could affect the types of technologies developed and adopted by firms, and have a large effect through this channel. This possibility was first raised by Wood (1994), who argued that trade with the LDCs will lead to *defensive skill-biased innovations*. Wood, however, did not develop the mechanism through which such defensive innovations could occur. I now illustrate how trade causes skill-biased technical change using the endogenous technology model developed in section 5.2 (this analysis draws on Acemoglu 1999b).

Suppose that the United States starts trading with the LDCs as discussed above, and assume that the LDCs always use U.S. technologies. Therefore, the supply of skilled and unskilled goods in the LDCs is $Y_h = A_h\hat{H}$ and $Y_l = A_l\hat{L}$ where as before $\hat{H}/\hat{L} < H/L$. The immediate effect will be an increase in the relative price of skill-intensive goods as illustrated by

[51] This is probably the weakest criticism against the trade view, and many studies have pointed out how international trade could have a larger effect on U.S. labor market prices in the presence of labor market rents. For example, George Borjas and Valerie Ramey (1995), Dani Rodrik (1997), and Dube and Reddy (1999) have argued that the threat of international trade may reduce wages, especially in sectors with substantial rents, and this change in bargaining power may affect the earnings of unskilled workers more, increasing inequality.

equation (27). Now, recall from the analysis in section 5.2 that there is a relative price effect on the direction of technical change (because developing technologies to produce the more expensive good is more profitable). Therefore, trade, by making the skill-intensive goods more expensive, encourages more skill-biased technical change.

To determine exactly how the direction of technical change will be affected by trade, we need to know the market sizes for new technologies after trade opening. It is plausible to assume that trade opening with the LDCs will not have a major effect on the enforcement of intellectual property rights in the South. In that case, trade opening will induce skill-biased technical change in the United States. Specifically, as long as after trade opening the United States does not start producing technologies for unskilled workers in the LDCs, the relative market sizes for the two types of technologies remain at H/L. This implies that the technology market clearing condition, equation (18), no longer holds. In particular, since $p_h^W H > p_l^W L$ from equation (27), there will now only be incentives for skill-biased technical change. This process continues until $p^W = p_h^W / p_l^W = (H/L)^{-1}$, so that incentives to develop the two different types of technologies are balanced. This implies that the skill bias of technical change is still determined by equation (18) from section 5.2, i.e., by U.S. domestic relative supplies alone. Intuitively, the relative price of skill-intensive goods plays two roles in this model. The first is to clear the market for goods (i.e., equation 27), and the second is to ensure equilibrium in the technology market (cfr. equation 18). Since the technology market clearing condition relates the relative price of skill-intensive goods to the relative supplies in the U.S. market, which do not change, the long-run equilibrium price of skill-intensive goods cannot change either. Combining equations (18) and (27) gives the post-trade skill bias of technology as

$$\frac{A_h^W}{A_l^W} = \left[\frac{(H+\hat{H})}{(L+\hat{L})}\right]^{-1} \left(\frac{H}{L}\right)^{1/(1-\rho)} > \frac{A_h^{US}}{A_l^{US}} = \left(\frac{H}{L}\right)^{\rho/(1-\rho)}$$

where A_h^{US}/A_l^{US} is the pre-trade skill bias of technology in the United States.

The implication is that when the direction of technical change is endogenous, trade between the United States and the LDCs will induce skill-biased technical progress. The result is not only that trade leads to an increase in skill premia, but that this can happen without the counterfactual implications of the standard trade models discussed above.

The first implication of this induced skill bias is that the impact of trade on labor markets may be much larger than predicted by the standard trade models, which helps against the criticism that the amount of trade the United States undertakes with the LDCs is not large enough. Second, because trade causes skill-biased technical change, the fact that all sectors have increased the employment of skilled workers is consistent with trade being the underlying cause of the increase in inequality. Third, for the same reason, there is a force counteracting the decline in inequality in the LDCs implied by trade: these economies use U.S. technologies, which are becoming more skill-biased. Finally, and quite strikingly, trade leaves the relative price of skill-intensive goods in the United States unchanged in the long-run. Recall that changes in relative prices are the usual intervening mechanism in trade models, so a number of studies have concluded that trade has not been an important factor in the increase in inequality because the relative price of skill-intensive goods has not increased much (e.g., Lawrence and Slaughter 1994; Sachs and Shatz 1995). In this model, the long-run relative price of skill-intensive goods in the United States is unaffected by trade. More generally, induced skill-biased technical change in the United States implies that trade will increase the price of skill-intensive goods by only a limited amount, while still having a major effect on the U.S. labor market.

Notice finally that the interaction between international trade and technical change may help to explain the decline in the wages of low-skill workers. Increased international trade acts as an increase in the supply of unskilled workers, and as shown in our basic framework in section 3, this would put downward pressure on unskilled wages. Borjas, Freeman, and Katz (1987), for example, provide evidence that increased international trade during the 1980s reduced the wages of high school graduate workers (though they also suggest that the effect of the immigration of less-skilled workers was greater).

Overall, international trade could still be a major driving force of the changes in the wage structure. However, for increased trade to have such a large effect on the structure of wages—and to avoid the aforementioned counterfactual implications—it must cause a change in the path of technological progress. So the combination of trade opening and endogenous technical change gives an alternative theory for acceleration: skill-biased technical change accelerates, neither exogenously nor in response to the changes in the supply of skilled workers, but due to trade opening.

7. *Changes in Residual Inequality*

The previous sections highlighted that there are major unanswered questions regarding the causes of the increase in inequality, the reasons for the faster skill-biased technical change in the past few decades, and the determinants of the fall in the wages of low-skill workers. These questions awaiting further research notwithstanding, we have a reasonably simple and useful framework, and the beginnings of consistent answers. In contrast, in this and the next section, I discuss areas where answers are much more tentative, and there is a greater need for future research. I begin with residual inequality. A major issue that most models discussed so far failed to address is the differential behavior of returns to schooling and residual inequality during the 1970s. I argue in this section that an explanation for this pattern requires models with multi-dimensional skills.

7.1 *A Single Index Model of Residual Inequality*

The simplest model of residual inequality is a single index model, in which there is only one type of skill, though this skill is only imperfectly approximated by education (or experience). Expressed alternatively, in a single index model observed and unobserved skills are perfect substitutes. Consider, for example, the model developed above, but suppose that instead of skills, we observe education, e.g., whether the individual is a college graduate, which is imperfectly correlated with true skills. A fraction ϕ_c of college graduates are highly skilled, while a fraction $\phi_n < \phi_c$ of noncollege graduates are highly skilled. Denote the skill premium by $\omega = w_H/w_L$. The college premium, i.e., the ratio of average college to noncollege wages, is

$$\omega^c = \frac{w_C}{w_N} = \frac{\phi_c w_H + (1-\phi_c) w_L}{\phi_n w_H + (1-\phi_n) w_L} = \frac{\phi_c \omega + (1-\phi_c)}{\phi_n \omega + (1-\phi_n)},$$

while within-group inequality, i.e., the ratio of the wage of high-wage college graduates (or noncollege graduates) to that of low-wage college graduates (or noncollege graduates), is $\omega^{within} = \omega$ (since high-wage workers in both groups earn w_H, while low-wage workers earn w_L). As long as ϕ_c and ϕ_n remain constant, ω^c and ω^{within} will always move together. Therefore, an increase in the returns to observed skills—such as education—will also be associated with an increase in the returns to unobserved skills.

This framework provides a natural starting point, linking between- and within-group inequality. It predicts that within- and between-group inequality should move together. But during the 1970s, returns to schooling fell while residual (within-group) inequality increased sharply. We can only account for this fact by positing a decline in ϕ_c relative to ϕ_n of a large enough magnitude to offset the increase in ω; this would ensure that during the 1970s the college premium could fall despite the increase in within-group inequality. A large decline in ϕ_c relative to ϕ_n would predict a very different behavior of the college premium within different cohorts. Yet the appendix shows little evidence in favor of this. I therefore conclude that the single index model cannot explain the changes in residual inequality during the 1970s and the 1980s.

7.2 *Sorting and Residual Inequality*

Another approach would combine educational sorting with an increase in the demand for skills. Suppose that wages are given by $\ln w_{it} = \theta_t a_i + \gamma_t h_i + \varepsilon_{it}$ where h_i is a dummy for high education, a_i is unobserved ability, and ε_{it} is a mean zero disturbance term. Here γ_t is the price of observed skills, while θ_t is the price of unobserved skills. The education premium can be written as

$$\ln \omega_t \equiv E(\ln w_{it} \mid h_{it} = 1) - E(\ln w_{it} \mid h_{it} = 0) = \gamma_t + \theta_t (A_{1t} - A_{0t})$$

where $A_{1t} \equiv E(\ln w_{it} \mid h_{it} = 1)$ and A_{0t} is defined similarly. Residual inequality can be measured by $Var(A_{it} \mid h = 0)$ and $Var(A_{it} \mid h = 1)$.

To simplify the discussion, assume that there is perfect sorting into education, in the sense that there exists a threshold $\bar{a}$ such that all individuals with unobserved ability above $\bar{a}$ obtain education. Then within-group inequality among high and low-education workers will move in opposite directions as long as the price of observed skills, θ, is constant: as $\bar{a}$ declines (and average education increases), $Var(A_{it} \mid h = 1)$ will increase, but $Var(A_{it} \mid h = 0)$ will fall. Intuitively, there are more and more "marginal" workers added to the high-education group, creating more unobserved heterogeneity in that group and increasing within-group inequality. But in contrast, the low-education group becomes more homogeneous. Therefore, without a change in the prices for unobserved skills, this approach cannot account for the simultaneous increase in inequality among both low- and high-education groups.[52]

7.3 *Churning and Residual Inequality*

Another approach emphasizes that workers of all levels of education may face difficulty adapting to changes. This

[52] A natural variation on this theme would be a situation in which γ and θ move together. However, this will run into the same problems as the single index model: if γ and θ always move together, then such a model would predict that within-group inequality should have fallen during the 1970s. Therefore, models based on sorting also require a mechanism for the prices of observed and unobserved skills to move differently during the 1970s.

has been argued by Piore and Sabel (1984), and more recently by Aghion, Howitt, and Violante (2000) and Gould, Moav, and Weinberg (2000). Violante (2000) offers an alternative, but related theory, where increased churning is driven by the greater productivity gap between different firms (because of faster embodied technical change) and increased skill dynamics of ex ante identical workers (which he contrasts with the argument that it is innate ability differences that matter). According to all these approaches, an increase in inequality results from more rapid technical change, not because of skill bias but because of increased "churning" in the labor market. Aghion, Howitt, and Violante (2000), for example, suggest that only some workers will be able to adapt to the introduction of new technology, and this will increase wage inequality.

An advantage of this approach is that it is in line with the increased earnings instability pointed out by Gottschalk and Robert Moffit (1994). However, there is relatively little evidence, other than this increase in earnings instability, supporting the notion that there is more churning in the labor market. The data on job creation and job destruction reported by Steven Davis, John Haltiwanger, and Scott Schuh (1996) shows no increase in job reallocation during the 1980s or the early 1990s, and most evidence does not indicate much of a decline in job stability over this period (e.g. Francis Diebold, David Neumark, and Daniel Polsky 1997; or Henry Farber 1995).[53] Also theories based on churning do not naturally predict a divergence between returns to education and residual inequality during the 1970s. Therefore, a mechanism that could lead to differential behavior in the prices to observed and unobserved skills is still necessary.[54]

7.4 *A Two-Index Model of Residual Inequality*

Since models based on a single index of skill (or models where different types of skills are perfect substitutes) are inconsistent with the differential behavior of returns to schooling and within-group inequality during the 1970s, an obvious next step is to consider a two-index model where observed and unobserved skills are imperfect substitutes. There are good reasons to expect that in the real world skills are multidimensional. For example, the social psychologist Howard Gardner (1988) makes a strong case that we should always think of skills as multidimensional, and that the standard IQ measures fail to capture this multidimensionality. There is a long tradition in economics building on the Roy model which uses models with multidimensional skills to analyze wages and returns to schooling (e.g., Robert Willis and Sherwin Rosen 1975). In the context of the determinants of earnings, a recent paper by Bowles, Gintis, and

[53] More recent evidence indicates that there may have been a decrease in job tenure during the later parts of the 1990s (see Neumark, Polsky, and Daniel Hansen 1999).

[54] An interesting theory similar to the churning models that could lead to such a differential behavior is advanced by Galor and Tsiddon (1997). They draw a distinction between ability and education, and argue that returns to ability increase faster during periods of rapid technological change. If we view the 1970s as a period of rapid technological change, as suggested above, this theory would imply an increase in the returns to ability (unobserved skills) during this period. Nevertheless, this explanation is still not consistent with the facts because high-ability individuals are more likely to be high education, so rapid technological progress should also increase returns to schooling. Perhaps a combination of this mechanism with differential sorting into education, or with imperfect substitution between high- and low-education workers, might be able to account for the divergence between returns to schooling and residual inequality during the 1970s, but such a model has not been developed yet.

Osborne (2001) also forcefully argues that there are many dimensions to skills including the ability to function in hierarchies and other social situations. To discuss these issues, I now consider a simple two-index model (see Acemoglu 1998). Suppose that there are four types of workers, differentiated by both education and unobserved skills. The economy has an aggregate production function

$$Y = [(A_{lu}L_u)^\rho + (A_{ls}L_s)^\rho + (A_{hu}H_u)^\rho + (A_{hs}H_s)^\rho]^{1/\rho},$$

where L_u is the supply of low-skill low-education workers, and other terms are defined similarly. Within-group inequality corresponds to the ratio of the wages of skilled low-education workers to those of unskilled low-education workers, and/or to the ratio of the wages of skilled high-education workers to those of unskilled high-education workers. A natural starting point is to presume that the fraction of high-skill workers in each education group is constant, say at $\phi_l = L_s/L_u$ and $\phi_h = H_s/H_u > \phi_l$, which implies that there are more high-ability workers among high-education workers. With this assumption, within-group inequality will be

$$\frac{w_{Ls}}{w_{Lu}} = \left(\frac{A_{ls}}{A_{lu}}\right)^\rho \phi_l^{-(1-\rho)} \quad \text{and} \quad \frac{w_{Hs}}{w_{Hu}} = \left(\frac{A_{hs}}{A_{hu}}\right)^\rho \phi_h^{-(1-\rho)}. \tag{29}$$

The college premium, on the other hand, is

$$\omega = \frac{\phi_h^\rho A_{hs}^\rho + A_{hu}^\rho}{\phi_l^\rho A_{ls}^\rho + A_{lu}^\rho} \left(\frac{1+\phi_l}{1+\phi_h}\right)^\rho \left(\frac{H}{L}\right)^{-(1-\rho)}.$$

Using this framework and the idea of endogenous technology, we can provide an explanation for the differential behavior of returns to schooling and within-group inequality during the 1970s. Recall that according to the endogenous technology approach, it is the increase in the supply of more-educated workers that triggers more rapid skill-biased technical change. Because technology adjusts sluggishly, the first effect of an increase in the supply of educated workers, as in the 1970s, will be to depress returns to schooling. This will continue until technology has changed enough to offset the direct effect of the higher supply of skills (see figure 7). This change in returns to schooling has no obvious implication for within-group inequality in a multi-skill set-up, since it is the education skills that are becoming abundant, not unobserved skills—in fact, in equation (29), within-group inequality is invariant to changes in the supply of educated workers unless there is a simultaneous change in ϕ_h and ϕ_l.

Under the plausible assumption that more skilled workers within each education group also benefit from skill-biased technical progress, technical change spurred by the increase in the supply of educated workers will immediately benefit workers with more unobserved skills, raising within-group inequality. Therefore, an increase in the supply of educated workers will depress returns to schooling, while increasing within-group inequality. After this initial phase, technical change will increase both returns to schooling and within-group inequality.[55]

[55] If the 1960s are also characterized by steady skill-biased technical change, equation (29) suggests that there should have been an increase in residual inequality during this decade as well. The data presented in section 2 do not support this prediction. Therefore, it seems that to explain the basic trends, one needs to posit that improvements in technology take the form $\ln A_j(t) = \gamma'_j + \gamma_j \cdot t$ with $\gamma_{hs} = \gamma_{hu} > \gamma_{ls} = \gamma_{lu}$ during regular times, but when there is an acceleration in skill bias, the pattern changes to favor workers with more unobserved skills, i.e., $\gamma_{hs} > \gamma_{hu}$ and $\gamma_{ls} > \gamma_{lu}$. Although this assumption can generate stable residual inequality before the 1970s, and an increase in residual inequality during the 1970s, it is simply *reverse engineered* to fit the facts. Future research to investigate whether there are natural reasons for this pattern to arise would be useful.

Overall, single index models are not capable of explaining the changes in residual inequality over the past thirty years, and we do not yet know how important various factors are. Analysis of the determinants of residual inequality and the reasons why there was an explosion in overall inequality beginning in the 1970s remains a major research area.

8. *Cross-Country Patterns*

So far, I have focused on U.S. wage inequality patterns and on the incentives to develop new technologies coming from the U.S. supply of skills. The cross-country dimension presents a number of challenges, in particular because it is difficult to explain why inequality increased much more in some countries than others. In addition, for the endogenous technology view, it is important to know whether it is the relative supply of skills in each country or in the world as a whole that determines the direction of technical change. I now briefly discuss these issues.

8.1 *Differences in Inequality Patterns*

Although the tendency toward greater inequality has been a feature in many developed and less developed countries (see Freeman and Katz 1995; and Berman and Machin 2000), there are also marked differences in the behavior of within- and between-group inequality across these countries. Katz, David Blanchflower, and Gary Loveman (1995), Murphy, Riddell, and Romer (1998), and Card and Lemieux (2000) show that the differential behavior of the supply of skills can go a long way toward explaining the differences in the returns to schooling, especially between the United States, Canada, and the United Kingdom. Nevertheless, it is puzzling that wage inequality increased substantially in the United States and the United Kingdom, but remained fairly stable in many continental European economies (see for example Davis 1995; Gottschalk and Timothy Smeeding 1999).

The standard explanation for this divergent behavior, succinctly summarized by Krugman (1994) and OECD (1994), and sometimes referred to as the Krugman hypothesis, maintains that inequality did not increase as much (or not at all) in Europe because labor market institutions there encourage wage compression, limiting the extent of inequality. This can be captured in the competitive framework of section 3, where firms are always along their relative demand curve, by assuming that labor market institutions impose an exogenous skill premium $\bar{\omega} = w_H/w_L$. This implies:

$$\frac{H}{l} = \left(\frac{A_h}{A_l}\right)^{\rho/(1-\rho)} \bar{\omega}^{-1/(1-\rho)}. \qquad (30)$$

where the level of employment of unskilled workers, l, will generally be less than their labor supply L because of wage compression. A more compressed wage structure—i.e., a lower $\bar{\omega}$—will increase the unemployment of unskilled workers, given by $L - l$.

The view that wages are more compressed in Europe clearly has some merit. Francine Blau and Lawrence Kahn (1995) show that the major difference in overall inequality between the United States and many continental European economies is not in the 90–50 differential, but in the 50–10 differential. This suggests that the minimum wage, strong unions, and generous transfer programs in Europe are in part responsible for the relative wage compression in Europe.

Nevertheless, the Krugman hypothesis runs into two difficulties. First, unless there are extremely rigid institutions that fix the skill premium exogenously, skill-biased technical change should increase wage inequality irrespective of the degree of exogenously imposed wage compression. In contrast, in many continental European economies, most notably in Germany, wage inequality was very stable (see, e.g., Freeman and Katz 1995).

Second, the Krugman hypothesis makes an explicit prediction: profit-maximizing employment decisions of firms should lead to a decline in the employment of unskilled workers relative to that of skilled workers. In fact, skill-biased technical change might even reduce the unemployment rates of skilled workers. Yet, in Europe, the unemployment of skilled and unskilled workers increased together (e.g. Stephen Nickell and Brian Bell 1996; Krueger and Pischke 1997), and unskilled employment did not grow faster in the United States than in European economies (Card, Kramartz, and Lemieux 1996; Krueger and Pischke 1997).

It is possible that bargaining arrangements in Europe between firms and unions, imply not only wage compression, but also deviations from the relative demand curve for "skills" given by (30). This may be because European institutions force firms to pay uniform wages to all educated workers irrespective of their exact skills (marginal product), making the employment of skilled workers less profitable as well. Alternatively, if unions represent both skilled and unskilled workers, and are committed to wage compression, they may not want to suffer a large decrease in the employment of unskilled workers, and prefer to make certain concessions in wage levels in order to induce firms to employ more unskilled workers at a compressed wage structure. Although such deviations from equation (30) are a possibility, we have no direct evidence to assess how far off the relative demand curve European economies may be, and how they would respond to skill-biased technical change when they are away from the relative demand curve for skills.[56]

My preferred approach to explaining cross-country differences is to consider the effect of labor market institutions on technology choices. In particular, the European labor market institutions, which compress the structure of wages, will give greater incentives to adopting labor-complementary technologies, and will reinforce wage compression. I give a simple example to illustrate the point here. Suppose the productivity of a skilled worker is $A_h = a\eta$, whereas the productivity of an unskilled worker is $A_l = a$, where a is a measure of aggregate technology in use, and $\eta > 1$. Suppose that wages are determined by rent sharing, unless they fall below a legally mandated minimum wage, in which case the minimum wage binds. Hence, $w_j = \min\{\beta A_j, \underline{w}\}$, where $j = l$ or h, and β is worker's share in rent sharing. Note that the cost of technology upgrading does not feature in this wage equation, because rent sharing happens after technology costs are sunk. To capture wage compression, suppose the minimum wage is binding for unskilled workers in Europe. Now consider technology adoption decisions. In particular,

[56] An alternative view suggested by Nickell and Bell (1996) explains the differences in the wage structure across countries by differences in the skill distribution. According to this view, because of the relative weakness of the U.S. high school system, American noncollege workers are less skilled than their European counterparts. However, recent work by Dan Devroye and Freeman (2001) shows that differences in skill distribution have little to do with cross-country differences in wage dispersion. They document that dispersion of internationally comparable test scores among native-born Americans are similar to those in Europe, but wage inequality among native-born Americans is much higher.

firms can either produce with some existing technology, a, or upgrade to a superior technology, $a' = a + \alpha$, at cost γ. The profit to upgrading the technology used by a skilled worker is $(1 - \beta)\alpha\eta - \gamma$, both in the United States and Europe. The new technology will therefore be adopted when

$$\gamma \leq \gamma^S \equiv (1 - \beta)\alpha\eta.$$

Note that there is a holdup problem, discouraging upgrading: a fraction β of the productivity increase accrues to the worker due to rent sharing (Paul Grout 1984; Acemoglu 1996).

The incentives to upgrade the technology used by unskilled workers, on the other hand, differ between the United States and Europe. In the United States, this profit is given by $(1 - \beta)\alpha - \gamma$. So, the new technology will be adopted with unskilled workers if

$$\gamma \leq \gamma^U \equiv (1 - \beta)\alpha.$$

Clearly, $\gamma^U < \gamma^S$, so adopting new technologies with skilled workers is more profitable. The returns to introducing the new technology are different in Europe because the minimum wage is binding for unskilled workers. To simplify the discussion, suppose that even after the introduction of new technology, the minimum wage binds, i.e., $\underline{w} > \beta(A + \alpha)$. Then, the return to introducing the new technology in Europe with unskilled workers is $\alpha - \gamma$, and firms will do so as long as $\gamma < \alpha$. Since $\alpha > \gamma^U$, firms in Europe have greater incentives to introduce advanced technologies with unskilled workers than in the United States. This is because the binding minimum wage in Europe makes the firm *the full residual claimant* of the increase in the productivity of unskilled workers. This highlights that in an economy with a compressed wage structure, firms may have a greater incentive to increase the productivity of unskilled workers (see Acemoglu and Pischke 1999 for this argument in the context of training).

As long as the cost of upgrading to the new technology, γ, is small, i.e., less than γ^U, firms will upgrade both with skilled and unskilled workers in the United States and Europe. In this case, cross-country inequality levels will be stable. This corresponds to the situation in the 1950s and the 1960s. In contrast, if γ is high, for example, because the technological improvements of the 1980s are more expensive to implement, there may be a divergence in inequality between the two economies. For instance, if $\gamma \in (\gamma^U, \alpha)$, then new technology will not be adopted with unskilled workers in the United States, but it will be used with unskilled workers in Europe. As a result, while wage inequality increases in the United States, it will remain stable in Europe. Therefore, a simple story for cross-country differences in inequality trends emerges from this model: wage compression encourages the use of more advanced technologies with unskilled workers, and acts to reinforce itself in Europe. In contrast, technological developments can harm the earnings of low-skill U.S. workers who are not protected by this type of wage compression. Whether the interaction between wage compression and technology choice could be important in explaining European inequality and unemployment patterns is an area for future study.

8.2 *International Determinants of Technology*

The endogenous technology framework developed above links the skill bias of technology to the relative supply of skills. There are a number of interesting and difficult issues that arise when we consider the international dimension. Here I simply mention some preliminary approaches, but clearly much theoretical and empirical work remains to be done.

A first extension of the endogenous technology idea to an international context might be to suppose that skill bias in each country is determined by the country's relative supply of skills. Yet it may be more plausible to imagine a situation where new technologies spread across countries. In this case, it may be the incentives in the technologically most advanced country (the technological leader) that determine the skill bias of world technologies. This description may be adequate for understanding the skill bias of technologies used by less developed countries (see for example Acemoglu 1999b). But it is also possible for other technologically advanced economies to pursue a different path of technological development than the leader, in which case domestic incentives may be important in shaping skill bias.

What determines the skill bias of technologies developed by the technological leader? This depends on the market sizes for different types of technologies, hence on the international enforcement of intellectual property rights. For example, in the discussion on the effect of trade on technology, I supposed that there were no intellectual property rights for United States companies enforced in less developed economies. In this case, incentives to develop new technologies are shaped by the United States (or OECD) supplies. This may be a good starting point, since even when property rights are enforced, there will be a number of difficulties facing U.S. companies marketing their technologies in other countries, especially in the case of technologies that will be used with relatively low-skill workers. For example, technologies may need to be adapted to conditions in local markets, or producers in LDCs may be unable to pay for these technologies because of credit problems.

It is also worth noting that even when a country is using U.S. technologies, its effective skill bias may be influenced by its domestic skill supply. This is because U.S. technologies need to be adapted to local conditions, and firms will have a greater incentive to do this when there is a larger supply of workers to use these technologies. So it may be not only technological change that is endogenous to relative supplies, but also *technology adoption*.

Finally, another interesting cross-country dimension comes from looking at wage inequality trends in LDCs. As discussed in section 6.3, the first-order predictions of the standard trade theory are not borne out: instead of a decline in inequality, which would have been expected due to the greater integration of these economies into world trade, inequality increased in most LDCs. A recent paper by Berman and Machin (2000) shows an interesting pattern: while there has been rapid skill upgrading in many middle income countries, there is much less evidence for rapid skill upgrading in the poorest economies. A possible explanation for these patterns is that middle income countries are adopting advanced technologies much more rapidly than the poorest countries, and since these technologies are more skill-biased, these economies are undergoing rapid skill upgrading and increases in inequality. Furthermore, if, as claimed by Acemoglu and Zillibotti (2001), new technologies developed in the rich economies are typically "too skill-biased" for LDCs, the recent acceleration in skill bias could have negative implications for the LDCs. More generally, the impact of technologies developed in the advanced economies on LDC labor markets is an area that requires further research.

9. *Conclusion*

This essay discussed the link between technical change and the labor market, with special emphasis on the recent changes in the U.S. wage structure. In this process, I surveyed part of the large literature on the determinants of the rise in inequality, and put forth a different interpretation of the changes in technologies and their impact on the labor market than the most widely accepted view. It is difficult to summarize this large literature, and therefore, even more difficult to summarize this essay. Nevertheless, it may be useful to reiterate some of the main points:

1. The behavior of wages and returns to schooling in the United States indicates that technical change has been skill-biased during the past sixty years, and probably for most of the twentieth century.
2. Though more controversial, the evidence also points to an acceleration in skill bias during the past few decades.
3. In contrast, much of what we know suggests that technical change was not skill-biased during the nineteenth century, and most likely, it was skill-replacing.
4. We can understand the behavior of technical change by recognizing that the development and use of technology respond to profit incentives. When developing skill-biased techniques is more profitable, new technology will tend to be skill-biased. According to this perspective, the early nineteenth century was characterized by skill-replacing developments because the increased supply of unskilled workers in the English cities made the introduction of these technologies profitable.
5. In contrast, the twentieth century has been characterized by skill-biased technical change because the rapid increase in the supply of skilled workers has *induced* the development of skill-complementary technologies.
6. The acceleration in skill-biased technical change is then likely to have been a response to the rapid increase in the supply of skills during the past several decades, though this perspective does not suggest that we are necessarily in the midst of a "Technological Revolution"; what has changed is not necessarily the overall rate of progress, but the types of technologies that are being developed.
7. The recent technological developments are also likely to have affected the organization of the labor market—including the way firms organize production, labor market policies, and the form of labor market "institutions"—and may have had a large effect on the structure of wages through this channel.

Many of these conclusions are tentative. There is much research to be done to understand the process of technical change and how it impacts the labor market. In particular, what determines wage differences among observationally similar workers, why the trajectories of the Anglo-Saxon and continental European economies have diverged, and how technical change and institutional change interact are important areas for future research.

Appendix

A1. *Data Sources*

The samples are constructed as in Katz and Autor (2000). I thank David Autor for providing me with data from this study. Data from 1939, 1949, and 1959 come from 1940, 1950, and 1960 censuses. The rest of the data come from 1964–97 March CPSs. The college premium is the coefficient on workers with a college degree or more relative to high school graduates in a log weekly wage regression. The regression also includes dummies for other education categories, a quartic in experience, three region dummies, a nonwhite dummy, a female dummy, and interactions between the female dummy and the nonwhite dummy

TABLE A1
ANNUALIZED CHANGES IN OVERALL AND RESIDUAL WAGE INEQUALITY (FROM KATZ AND AUTOR)

	Census		March CPSs		May CPSs (ORGs)	
	90–10	50–10	90–10	50–10	90–10	50–10
Changes in overall inequality						
1960s	0.10	0.03	–0.03	–0.11	—	—
1970s	0.10	0.11	0.10	0.11	0.01	0.10
1980s	0.17	0.06	0.20	0.09	0.26	0.10
1990s	—	—	0.11	–0.03	0.05	0.00
Changes in residual inequality						
1960s	0.03	0.01	–0.01	–0.01	—	—
1970s	0.09	0.05	0.11	0.08	0.11	0.08
1980s	0.07	0.02	0.12	0.06	0.15	0.08
1990s	—	—	0.07	0.03	0.06	0.02

Note: The numbers give 10 × annualized changes from Table 4 of Katz and Autor (2000). 90–10 is the difference between the 90th and 10th percent of the log wage or residual distribution, and 50–10 is the difference between the median and 10th percent of the corresponding distribution. The residuals are estimated from log earnings regressions with nine education dummies, a quartic in experience and their interactions. See notes to Tables 3 and 4 in Katz and Autor (2000).

and the experience controls. The sample includes all full-time full-year workers between the ages of 18 and 65, and except those with the lowest 1 percent earnings. Earnings for top coded observations are calculated as the value of the top code times 1.5. The relative supply of skills is calculated from a sample that includes all workers between the ages of 18 and 65. It is defined as the ratio of college equivalents to non-college equivalents, calculated as in Autor, Katz, and Krueger (1998) using weeks worked as weights. In particular, college equivalents = college graduates + 0.5 × workers with some college, and noncollege equivalents = high school dropouts + high school graduates + 0.5 × workers with some college.

Samples used for overall and residual wage inequality include only white male full-time full year workers between the ages of 18 and 65, and exclude those earning less than half the real value of the 1982 minimum wage converted from nominal dollars using the personal consumption expenditure deflator (see Katz and Autor 2000). Earnings for top coded observations are calculated as the value of the top code times 1.5.

A2. *The Behavior of Overall Inequality During the 1970s*

In an important paper on the effect of labor market institutions on inequality, DiNardo, Fortin, and Lemieux (1995) provide evidence suggesting that in the May CPSs, there is no increase in inequality during the 1970s. In table A1, I display numbers from the survey by Katz and Autor (2000), who report changes in residual inequality for the past four decades from three different sources: decennial censuses, and March CPSs and May CPSs (and later Outgoing Rotation Group files—ORGs). These numbers show no significant change in residual or overall inequality during the 1960s, and consistent increases in inequality from all sources during the 1970s and the 1980s. For example, the data from the Census and the March CPSs indicate that the 90–10 differential increased about 0.10 a year between 1970 and 1979, while the 50–10 differential increased by about 0.11 a year during the same period. The May CPS data show a smaller increase in the 90–10 differentials during this period, but a comparable increase in the 50–10 differential. Overall, although there is less uniformity among data sources regarding the behavior of residual inequality than returns to schooling (see Katz and Autor 2000), there is considerable evidence that residual and overall inequality started to increase during the 1970s.

A3. *Can Composition Effects Explain Inequality Changes?*

A possible explanation for the patterns we observe could be changes in the distribution of unobserved skills— or more concretely, *composition effects*. For example, the average ability of workers with high education may have increased relative to that of workers with low education over time. Here, I document that the increase in the returns to education and residual inequality are not smply due to composition effects. Note first that composition effects cannot by themselves explain the recent changes in inequality: as noted in subsection 7.2, composition effects suggest that inequality among educated and uneducated workers should

TABLE A2
COMPOSITION EFFECTS

Born in 19– Year ↓ →	06–10	11–15	16–20	21–25	26–30	31–35	36–40	41–45	46–50	51–55
Panel A										
1950	1.448	1.370	1.175	1.093						
1960	1.551	1.564	1.525	1.421	1.303	1.132				
1970			1.680	1.656	1.613	1.539	1.392	1.153		
1980					1.567	1.560	1.538	1.402	1.222	1.063
1990							1.798	1.761	1.723	1.674
Panel B										
$\Delta \ln \omega_{50-60}$	0.103	0.194	0.350	0.328						
$\Delta \ln \omega_{60-70}$			0.155	0.234	0.311	0.407				
$\Delta \ln \omega_{70-80}$					–0.047	0.021	0.146	0.249		
$\Delta \ln \omega_{80-90}$							0.260	0.359	0.500	0.611
Panel C										
$\Delta^2 \ln \omega_{50-70}$			0.051	0.040	–0.040	0.079				
$\Delta^2 \ln \omega_{60-80}$					–0.201	–0.213	–0.165	–0.158		
$\Delta^2 \ln \omega_{70-90}$							0.307	0.338	0.354	0.362

Note: The top panel gives the college premium from the census indicated at the beginning of the row for cohorts born in the five-year intervals indicated at the head of the column. For example, the first number is for individuals born between 1906–10 from the census of 1950. The college premium is defined as the wages of workers from that cohort with a college degree or more divided by the wages of workers from that cohort with twelve years of schooling. The bottom panel gives the change in the college premium for a given cohort between the two indicated dates and the difference between the wage growth of two neighboring cohorts as indicated by equations (34) and (35). All data are from the decennial censuses for white males born in the United States.

move in opposite directions. This suggests that changes in the true returns to skills have played at least some role in the changes in inequality.

More generally, to get a sense of how important composition effects may be, consider a variant of equation (13) above with two education levels, high $h = 1$ and low $h = 0$, and suppose wages are given by

$$\ln w_{it} = a_i + \gamma_t h_i + \varepsilon_{it} \tag{31}$$

where h_i is a dummy for high education, a_i is unobserved ability, and ε_{it} is a mean zero disturbance term. Define the (log) education premium—the difference between the average wages of high and low education workers—can be written as

$$\begin{aligned}\ln \omega_t &\equiv E(\ln w_{it} \mid h_i = 1) - E(\ln w_{it} \mid h_i = 0)\\ &= \gamma_t + A_{1t} - A_{0t}\end{aligned}$$

where $A_{1t} \equiv E(a_i \mid h_i = 1)$ and A_{0t} is defined similarly. The increase in the education premium can be caused by an increase in γ_t (a true increase in the returns to skills) or an increase in $A_{1t} - A_{0t}$. There are basically two reasons for an increase in $A_{1t} - A_{0t}$: (1) changes in cohort quality, or (2) changes in the pattern of selection into education.

Consider changes in cohort quality first. If, as many claim, the U.S. high school system has become worse, we might expect a decline in A_{0t} without a corresponding decline in A_{1t}. As a result, $A_{1t} - A_{0t}$ may increase. Alternatively, as a larger fraction of the U.S. population obtains higher education, it is natural that selection into education (i.e., the abilities of those obtaining education) will change. It is in fact possible that those who are left without education could have very low unobserved ability, which would translate into a low level of A_{0t}, and therefore into an increase in $A_{1t} - A_{0t}$.

Although these scenarios are plausible, theoretically the opposite can happen as well. For example, many academics who have been involved in the U.S. education system for a long time complain about the decline in the quality of universities, while the view that American high schools have become much worse is not shared universally (e.g., Krueger 1998). The selection argument is also more complicated than it first appears. It is true that, as long as those with high unobserved abilities are more likely to obtain higher education, an increase in education will depress A_{0t}. But it will also depress A_{1t}. To see why, assume that there is perfect sorting—i.e., if an individual with ability a obtains education, all individuals with ability $a' > a$ will do so as well. In this case, there will exist a threshold level of ability, $\bar{a}$, such that only those with $a > \bar{a}$ obtain education. Next consider a uniform distribution of a_i between b_0 and $b_0 + b_1$. Then,

$$A_0 = \frac{1}{\bar{a} - b_0}\int_{b_0}^{\bar{a}} a da = \frac{\bar{a} + b_0}{2}$$

and

$$A_1 = \frac{1}{b_1 - b_0 - \bar{a}}\int_{\bar{a}}^{b_0 + b_1} a da = \frac{b_0 + b_1 + \bar{a}}{2}.$$

So both A_0 and A_1 will decline when $\bar{a}$ decreases to $\bar{a}'$. Moreover, $A_1 - A_0 = b_1/2$, so it is unaffected by the decline in $\bar{a}$. Intuitively, with a uniform distribution of a_i, when $\bar{a}$ increases, both A_0 and A_1 fall by exactly the same amount, so the composition effects have no influence on the education premium. Clearly, with other distributions of ability, this extreme result will no longer hold, but it remains true that both A_0 and A_1 will fall, and whether this effect will increase or decrease the education premium is unclear. Overall, therefore, the effects of changes in composition on education premia is an empirical question.

Empirically, the importance of composition effects can be uncovered by looking at inequality changes by cohort (see McKinley Blackburn, David Bloom, and Freeman 1992; Juhn, Murphy, and Pierce 1993). To see this, rewrite equation (31) as

$$\ln w_{ict} = a_{ic} + \gamma_t h_{ic} + \varepsilon_{cit} \tag{32}$$

where c denotes a cohort—i.e., a group of individuals who are born in the same year. I have imposed an important assumption in writing equation (32): returns to skills are assumed to be the same for all cohorts and ages; γ_t—though clearly they vary over time. We can now define cohort specific education premia as

$$\ln \omega_{ct} \equiv E(\ln w_{ict} \mid h_i = 1) - E(\ln w_{ict} \mid h_i = 0) = \gamma_t + A_{1ct} - A_{0ct}$$

where $A_{1ct} \equiv E(a_{ic} \mid h_i = 1)$ and A_{0ct} is defined similarly. Under the additional assumption that there is no further schooling for any of the cohorts over the periods under study, we have $\ln \omega_{ct} = \gamma_t + A_{1c} - A_{0c}$, which implies

$$\Delta \ln \omega_{c,t'-t} \equiv \ln \omega_{ct'} - \ln \omega_{ct} = \gamma_{t'} - \gamma_t, \tag{33}$$

i.e., changes in the returns to education within a cohort will reveal the true change in the returns. Yet, the assumption that returns to skills are constant over the lifetime of an individual may be too restrictive. Murphy and Welch (1992), for example, show quite different age-earning profiles by education. Nevertheless, a similar argument can be applied in this case too. For example, suppose $\ln \omega_{cst} = \gamma_{st} + A_{1c} - A_{0c}$ for cohort c of age s in year t, and that $\gamma_{st} = \gamma_s + \gamma_t$ (this assumption is also not necessary, but simplifies the discussion). Then $\Delta \ln \omega_{c,t'-t} = \gamma_{s'} - \gamma_s + \gamma_{t'} - \gamma_t$, where obviously $s' - s = t' - t$. Now consider a different cohort, c'' that is age s' in the year t and age s in the year t''. Then $\Delta \ln \omega_{c'',t-t''} = \gamma_{s'} - \gamma_s + \gamma_t - \gamma_{t''}$. So, the true change in the returns to skills between the dates t'' and t' is

$$\Delta^2 \ln \omega \equiv \Delta \ln \omega_{c,t'-t} - \Delta \ln \omega_{c'',t-t''} = \gamma_{t'} - \gamma_{t''}. \tag{34}$$

Using data from the 1950–90 censuses, table A2 gives some of the single and double differences of cohort inequality for white men aged 26–55. The single differences show increases in the returns to

TABLE A3
CHANGES IN INEQUALITY BY COHORT
(FROM JUHN ET AL. 1993)

Panel A: 90–10 Differentials for Log Weekly Wages

Year of market entry	1964	1970	1976	1982	1988
1983–88					1.38
1977–82				1.27	1.38
1971–76			1.13	1.24	1.38
1965–70		1.08	1.12	1.29	1.42
1959–64	1.13	1.01	1.13	1.30	1.40
1953–58	1.02	1.07	1.16	1.32	1.43
1947–52	1.02	1.11	1.15	1.30	
1941–46	1.02	1.07	1.16		
1935–40	1.06	1.09			
1929–34	1.09				

Panel B: 90–10 Differentials for Log Wage Residuals

Year of market entry	1964	1970	1976	1982	1988
1983–88					1.09
1977–82				1.06	1.16
1971–76			.96	1.09	1.18
1965–70		.86	.96	1.12	1.23
1959–64	.92	.86	.98	1.12	1.21
1953–58	.88	.91	.99	1.15	1.26
1947–52	.89	.94	.99	1.14	
1941–46	.94	.94	1.05		
1935–40	.95	.98			
1929–34	.99				

Note: This table replicates Table 3 of Juhn, Murphy, and Pierce (1993). The top panel reports the 90–10 differential for log weekly wages of the cohorts that have entered the labor market in the corresponding six-year interval. Panel B gives the 90–10 differential for the residuals from a regression of log weekly wages on education controls.

college within most cohorts, with the exception of the years between 1970 and 1980. Therefore, these increases are likely to reflect differential age effects by education. In contrast, the numbers in panel C for the 1950–70 period show no increases, suggesting that the double difference does a good job of controlling for composition effects. The numbers for the 1960–80 period are negative, which likely reflect the decline in the college premium between 1960 and 1980. The final row gives the most important results of this table. The 1970–90 double differences are large and positive, suggesting that the true returns to education increased over this time period. Interestingly, despite the well-known evidence that the college premium increased faster for younger workers over the 1980s, the results in table A2 show that the true increase in returns to skills between 1970 and 1990 are comparable for cohorts born between 1936 and 1955. These results therefore indicate that the major component of the increase in that college premium during the 1980s and 1990s was changes in true skill prices, not composition effects.

Table A3, which replicates table 3 from Juhn, Murphy, and Pierce (1993), shows that the increase in overall and residual inequality cannot be explained by composition effects either. Panel A shows that the 90–10 differential for cohorts entering the market between 1935 and 1964 is approximately constant between 1964 and 1970, but increases sharply for each cohort between 1970 and 1976, and then increases further between 1982 and 1988. Panel B shows a similar picture for log wage residuals. These results suggest that the changes in the structure of wages observed over the past thirty years cannot be explained by pure composition effects, and reflect mainly changes in the true returns to observed and unobserved skills.

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