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COMPUTING INEQUALITY: HAVE COMPUTERS CHANGED THE LABOR MARKET?*

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This paper examines the effect of skill-biased technological change as measured by computerization on the recent widening of U. S. educational wage differentials. An analysis of aggregate changes in the relative supplies and wages of workers by education from 1940 to 1996 indicates strong and persistent growth in relative demand favoring college graduates. Rapid skill upgrading within detailed industries accounts for most of the growth in the relative demand for college workers, particularly since 1970. Analyses of four data sets indicate that the rate of skill upgrading has been greater in more computer-intensive industries.

I. INTRODUCTION

Overall wage inequality and educational wage differentials have expanded substantially in the United States since the late 1970s. Increases in the growth rate of the relative demand for more-skilled workers driven by a greater pace of skill-biased technological change [Bound and Johnson 1992] or rising globalization pressures [Wood 1994, 1998] have been offered as explanations for this pattern. Katz and Murphy [1992] also emphasize a substantial slowdown in the rate of expansion of the relative supply of more-educated workers from the 1970s to the 1980s. A complementary story for rising inequality focuses on the decline in unions, the real value of the minimum wage, and pay-setting norms that have historically served to compress the wage structure [DiNardo, Fortin, and Lemieux 1996].

The skill-biased technological change explanation for rising wage inequality has particular appeal to many labor market analysts.[1] Much econometric and case-study evidence indicates that the relative utilization of more-skilled workers is positively

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1. For example, technological change was viewed by a substantial margin as the leading single contributing factor to rising U. S. wage inequality in a poll of

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correlated with capital intensity and the implementation of new technologies both across industries and across plants within industries [Bartel and Lichtenberg 1987; Doms, Dunne, and Troske 1997; Levy and Murnane 1996]. These patterns strongly suggest that physical capital and new technologies currently appear to be relative complements with more-skilled workers. The continued increase in the relative utilization of nonproduction workers and more-educated workers within detailed industries and within establishments in the United States, despite the rising relative wages of these groups during the 1980s and 1990s, indicates strong within-industry and within-establishment demand shifts favoring the more-educated that is often interpreted as reflecting skill-biased technological change [Berman, Bound, and Griliches 1994; Dunne, Haltiwanger, and Troske 1996]. Similar patterns of within-industry increases in the proportion of "skilled" workers are apparent in most other OECD nations [Berman, Bound, and Machin 1998]. The recent spread of computers and computer-based technologies provides a visible possible culprit behind these patterns.

But two distinctive hypotheses concerning the role of technological change need to be distinguished. The first is that skill-biased technological change (associated with changes in production techniques, organizational changes, and capital-deepening) is an important driving force behind long-run secular increases in the relative demand for more-skilled workers. The second is that the impact of technological change on the relative demand for more-skilled workers *accelerated* in the 1980s generating the recent surge in educational wage differentials.[2] Technological change and capital-deepening appear to have been associated with increased demands for more-skilled workers for many decades implying that correlations of technology indicators and the usage of more-skilled workers in the 1980s do not necessarily imply an acceleration in the impact of skill-biased technological change.[3]

experts at a recent colloquium on the topic at the Federal Reserve Bank of New York [*Economic Report of the President* 1997, p. 175].

2. Mishel, Bernstein, and Schmitt [1997a, 1997b] make a similar point of distinguishing between these two hypotheses.

3. For example, Goldin and Katz [1996, 1998] show that capital-deepening, the diffusion of purchased electricity, and the introduction of continuous-process and batch methods of production greatly increased the relative demand for nonproduction workers and more-educated production workers in manufacturing from 1909 to 1929, but that wage differentials by skill did not increase during this period. They argue that the rapid increase in the supply of skills arising from the

Progress in evaluating the skill-biased technological change hypothesis for recent increases in U. S. educational wage differentials requires (1) using a framework that incorporates both shifts in the relative demand and relative supply of skills, (2) examining a sufficiently long time frame to determine whether factors viewed as important in the 1980s were absent in other periods with different relative wage movements, and (3) looking at the relations among observable technology indicators and skill upgrading over such a longer time frame. We attempt such an assessment in this study.

Reasonably consistent data on relative earnings and quantities of workers by educational attainment are available since 1940. Thus, we focus on the college/high school relative wage as a proxy for the relative price of "more-skilled" labor and study its relation to measured changes in the relative supply and implied changes in the relative demand for college-educated labor.[4]

We first present evidence on trends in the relative quantities, wages, and wage-bill shares of workers by education in the aggregate U. S. labor market from 1940 to 1996. A simple relative supply and demand framework is used to interpret these data. Substantial secular relative demand growth favoring college workers over the past five decades is necessary to reconcile an increase in the log college/high school wage differential of 0.25 (approximately 0.55 percent annually) from 1950 to 1996 with a more than threefold increase in the employment share of college graduates. The data are less clear on whether the trend rate of demand growth for more-educated workers has increased since the 1970s. Relative demand growth appears to have been more rapid than usual in the 1980s, but its pace appears to have slowed considerably in the 1990s. Our framework suggests that the relative demand for more-skilled workers grew more rapidly during the past 26 years (1970–1996) than during the previous three decades (1940–1970). This conclusion is sensitive to the inclusion of the 1940s, a decade of sharp wage compression, in the earlier era. Nevertheless, a substantial increase in the growth

high school movement prevented wage inequality from rising in the face of what appears to be a skill-biased technological revolution.

4. Rising educational wage differentials and within-group wage inequality are both substantial contributors to the growth in overall U. S. wage inequality since the late 1970s [Katz and Autor 1998; Mishel, Bernstein, and Schmitt 1997a, 1997b]. Although the college wage premium and within-group inequality move similarly during the 1980s, they are distinct outcomes and appear to have evolved somewhat differently in other periods. It should be remembered that we analyze changes in the college wage premium and not changes in overall wage inequality.

rate of the within-industry component of the relative demand for college workers is apparent from the 1960s to the 1970s, with this higher within-industry growth rate maintained into the 1980s and 1990s.

The diffusion of computers and related technologies and changes in the organization of work associated with effectively utilizing these technologies may be sufficiently widespread to have contributed to this pattern of more rapid within-industry skill upgrading in recent years. We use data from the October 1984, 1989, and 1993 Current Population Survey (CPS) Supplements to document the growing utilization of computers in the workplace. We discuss the mechanisms through which changes in the costs of information technology may affect relative skill demands and find that educational upgrading occurred more rapidly in industries with greater computer utilization in the 1980s and early 1990s.

We further explore the role of skill-biased technological change in the growth of the relative demand for more-skilled workers from 1960 to 1990 by linking data from multiple sources on industry workforce composition, physical capital intensity, research and development expenditures, computer investments, and (for manufacturing industries) trade penetration and foreign outsourcing variables. We consistently find for both the manufacturing and nonmanufacturing sectors that increases in the utilization of more-skilled workers are greater in the most computer-intensive industries, although it is not clear whether a causal interpretation of these relationships is appropriate.

II. The Relative Supply of and Demand for Skills, 1940–1996

To explore whether an explanation for the large expansion in U. S. educational wage differentials since the late 1970s appears to be driven by an acceleration of relative demand shifts favoring more-skilled workers, we put the recent experience into a longer-term perspective. We examine changes in the relative quantities and wages of workers by education from 1940 to 1996, the longest time period for which appropriate data are available.[5]

5. The 1940 Census of Population Public Use Micro Sample is the first nationally representative sample with information on both educational attainment and earnings.

We use the 1% Census Public Use Micro Samples (PUMSs) from 1940 to 1990 to measure changes in the college/high school wage differential and the educational attainment of the U. S. workforce. The Census data are supplemented with data from the Current Population Survey (CPS) Merged Outgoing Rotation Group (MORG) files from 1980, 1990, and 1996. Because major changes in the educational attainment question were introduced in 1990 in the Census but not until 1992 in the Current Population Survey, we use consistent data on educational attainment from the 1980 and 1990 CPSs to measure changes from 1980 to 1990. The changes in the education question and the complete redesign of the CPS starting in 1994 mean that there are even greater difficulties in measuring changes from 1990 to 1996. We present two estimates of 1990–1996 changes using the 1996 MORG combined with either the 1990 Census PUMS or the February 1990 CPS since both of these 1990 samples use the new CPS education question. But all reported changes from 1990 to 1996 should be treated with some caution given the lack of data comparability. The Data Appendix provides details on the samples used.

A. Overall Demand and Supply Shifts

Panel A of Table I shows the evolution of the educational composition of aggregate U. S. labor input (for those aged 18 to 65) measured in full-time equivalents (total hours worked) and of the log college/high school wage differential from 1940 to 1996.[6] (Appendix 1 presents the analogous trends in the educational composition of employment measured in bodies and of the total wage bill.) The educational attainment of the workforce has increased rapidly throughout the 56-year period examined. Table I documents a dramatic decline in the share of those with less than a high school degree and a more than fourfold increase in the share of hours worked of college graduates and those with some college. Despite the continuing large increase in the relative supply of more-educated workers, the log college/high school wage differential has grown substantially (by 0.25) since 1950. Thus, sharp secular increases in the relative demand for more-educated

6. The log college/high school wage premiums presented in Table I are estimates of the log hourly wage differential for college graduates (those with sixteen or more years of schooling) relative to high school graduates (those with exactly twelve years of schooling) adjusted for changes in the demographic compositions of the two groups and for changes in the distribution of years of schooling of college graduates.

TABLE I
LEVELS AND CHANGES IN THE EDUCATIONAL COMPOSITION OF EMPLOYMENT AND THE COLLEGE+/HIGH SCHOOL WAGE PREMIUM, 1940–1996

A. Full-time equivalent employment shares by education level (in percent) and log college+/high school wage premium

	High school dropouts	High school graduates	Some college	College graduates	College equivalents	Log college+/ HS wage
1940 Census	67.9	19.2	6.5	6.4	9.6	.498
1950 Census	58.6	24.4	9.2	7.8	12.4	.313
1960 Census	49.5	27.7	12.2	10.6	16.7	.396
1970 Census	35.9	34.7	15.6	13.8	21.6	.465
1980 Census	20.7	36.1	22.8	20.4	31.8	.391
1980 CPS	19.1	38.0	22.0	20.9	31.9	.356
1990 CPS	12.7	36.2	25.1	26.1	38.6	.508
1990 Census	11.4	33.0	30.2	25.4	40.6	.549
Feb. 90 CPS	11.5	36.8	25.2	26.5	39.1	.533
1996 CPS	9.4	33.4	28.9	28.3	42.7	.557

B. Changes in college/noncollege log relative wages and employment (100 × annual log changes)

	Wages	College graduate FTEs	College equivalent FTEs
1940–1950	−1.86	2.14	2.80
1950–1960	0.83	3.43	3.51
1960–1970	0.69	3.00	3.19
1970–1980	−0.74	4.69	5.26
1980–1990 (CPS-CPS)	1.51	2.88	2.94
1990–1996 (Cen-CPS)	0.40	2.40	1.47
1990–1996 (CPS-CPS)	0.40	1.51	2.52

Full-time Equivalent (FTE) shares are calculated for samples that include all workers ages 18–65 in paid employment (both wage and salary and self-employed workers) during the survey reference week for each Census and CPS sample. Usual weekly hours for CPS samples are imputed for the self-employed using average usual weekly hours for wage and salary workers in the same industry-education-year cell. FTE shares are defined as the share of total weekly hours supplied by each education group. Samples are drawn from the 1940, 1950, 1960, 1970, 1980, and 1990 Census PUMS; the 1980, 1990, and 1996 Merged Outgoing Rotation Groups (MORG) of the CPS; and the February 1990 CPS. College equivalents are defined as those with a college education plus half of those with some college. Noncollege (or high school) equivalents are those with twelve or fewer years of schooling (or high school diploma or less) plus half of those with some college.

The log college-plus/high school wage differential in each period is a weighted average of the estimated college (exactly sixteen years of schooling or a B.A. degree) and postcollege (17+ years of schooling or a postbaccalaureate degree) wage premium relative to high school workers (those with exactly 12 years of education or a high school diploma) in the indicated years, where the weights are the relative employment shares of college and postcollege workers in the 1980 Census (for Census samples) and 1980 MORG file (for CPS samples). The differentials are estimated with cross-section log hourly earnings regressions for wage and salary workers in each sample with dummies for single years of schooling, a quartic in experience, three region dummies, a part-time dummy, a female dummy, a nonwhite dummy, and interaction terms between the female dummy and the quartic in experience and the nonwhite dummy. In CPS samples, hourly earnings are calculated as the ratio of usual weekly earnings to usual weekly hours, and, in Census samples, as annual earnings divided by the product of weeks worked in the previous year and hours worked in the survey week. The February 1990 and 1996 college-plus/high school premiums are estimated for full-time workers only. Annualized log wage changes for the 1990–1996 period reported in the first column of panel B are based on the college-plus/high school differentials estimated from the February 90 CPS and 1996 CPS MORG samples. See the Data Appendix for details.

workers are essential to explain such a pattern in a supply-and-demand framework in which workers with different amounts of education are imperfect substitutes in production.[7]

Panel B of Table I displays annual rates of change in the relative earnings and quantity of college workers by decade. We summarize the relative quantity of labor by education by converting all workers into college and noncollege workers.[8] We use two different classification schemes: (1) college graduates and all other workers; and (2) college equivalents (college graduates plus half of those with some college) and high school equivalents (half of those with some college plus workers with twelve or fewer years of schooling). Our basic approach is to examine the relative wage of two "pure" skill groups (college graduates and high school graduates) and to relate the evolution of this relative wage to changes in the relative quantities and demands for "equivalents" of these pure skill classes.[9]

The sharp compression of educational wage differentials in the 1940s followed by an expansion in the 1950s despite more rapid growth in the relative quantity of more-educated workers in the 1950s suggests an acceleration on the demand side in the 1950s or a large role of institutional factors in the 1940s. In contrast, the large differences in changes in the college wage premium in the 1980s versus the 1970s may not require much change in demand behavior and could largely reflect sharp acceleration in the rate of growth of the relative supply of college workers in the 1970s with the baby boom cohorts combined with a

7. The large increases in the educational attainment of the U. S. workforce since 1940 may overstate increases in the relative supply of "more-skilled" workers to the extent that the "unobserved" quality of more-educated workers declines with some "relabeling" of "lower productivity" workers into higher education categories. A careful study by Juhn, Kim, and Vella [1996] examines this issue using Census PUMS data from 1940 to 1990 and finds that conclusions concerning changes in relative supply and implied relative demand shifts are not much affected by adjustments for such relabeling through controls for cohort-specific college share or mean years of education.

8. This two-labor-input framework clearly over simplifies the analysis of relative wage determination, but it leads to broad conclusions that are similar to more disaggregated approaches such as used by Katz and Murphy [1992] and Murphy and Welch [1992].

9. Welch [1969] examines the conditions under which it is reasonable to aggregate a large number of skill groups into a smaller number of pure skill classes. Katz and Murphy [1992] and Murphy and Welch [1993] closely follow Welch's "linear synthesis" approach by aggregating other education groups (those with some college and high school dropouts) into college equivalents and high school equivalents on the basis of the extent to which their wages track those of the pure skill groups. The resulting classification scheme is very similar to the college and high school equivalent measures used in this paper. Johnson [1997] takes a similar approach to ours in defining college and high school equivalent workers.

deceleration in the 1980s and 1990s with the baby bust cohorts [Katz and Revenga 1989; Katz and Murphy 1992; Murphy and Welch 1992].

Table II attempts to more formally assess alternative relative supply and demand shift scenarios for the observed pattern of changes in the relative wages and relative quantities by education from 1940 to 1996. We use a simple two-factor framework in which we assume an inelastic (predetermined) short-run relative supply function and a downward sloping relative demand function. Information on changes in the log ratio of the wage bill of college graduates to the wage bill of noncollege workers and on changes in the (composition-adjusted) relative wage of college graduates can be used to draw inferences concerning the rate of growth of the (composition-adjusted) relative supply and the relative demand for college graduates across time periods.

This point can be illustrated by considering a simple CES production function for aggregate output Q with two factors, college equivalents (c) and high school equivalents (h):

$$Q_t = [\alpha_t(a_tN_{ct})^{\rho} + (1 - \alpha_t)(b_tN_{ht})^{\rho}]^{1/\rho}, \tag{1}$$

where N_{ct} and N_{ht} are the quantities employed of college equivalents and high school equivalents in period t, a_t and b_t represent skilled and unskilled labor-augmenting technological change, α_t is a time-varying technology parameter that can be interpreted as indexing the share of work activities allocated to skilled labor, and ρ is time invariant. The aggregate elasticity of substitution between college and high school equivalents is given by $\sigma = 1/(1 - \rho)$. Skill-neutral technological progress raises a_t and b_t by the same proportion. Skill-biased technological change involves increases in a_t/b_t or α_t.

The aggregate production function given by (1) does not necessarily have any simple interpretation in terms of the production functions of individual firms or even industry-level production functions. The aggregate elasticity of substitution σ reflects not only technical substitution possibilities in firm-level production functions but also outsourcing possibilities and substitution possibilities across goods and services in consumption. Changes in the "technology" indicators a_t/b_t and α_t represent not only true technological changes at the firm level but also the nonneutral effects on skill groups of changes in the relative prices or quantities of nonlabor inputs (e.g., capital and energy) and shifts

TABLE II

College and College Equivalent Wage-Bill Shares, Supply and Demand Shifts, 1940–1996

A. Changes in college-plus/noncollege log relative wages, wage bill, and supply (100 × annual log changes)

		College graduates		College equivalents	
	Relative wage	Relative wage bill	Relative supply change	Relative wage bill	Relative supply change
1940–1950	−1.86	−0.37	1.49	0.50	2.35
1950–1960	0.83	3.76	2.93	3.75	2.91
1960–1970	0.69	3.35	2.65	3.25	2.55
1970–1980	−0.74	3.56	4.30	4.25	4.99
1980–1990	1.51	3.99	2.48	4.05	2.53
1990–1996 (Cen-CPS)	0.40	2.75	2.35	1.98	1.58
1990–1996 (CPS-CPS)	0.40	2.33	1.93	2.81	2.41

B. Implied relative demand shifts favoring college workers (100 × annual log changes)

	College graduates			College equivalents		
	$\sigma = 1$	$\sigma = 1.4$	$\sigma = 2$	$\sigma = 1$	$\sigma = 1.4$	$\sigma = 2$
1940–1950	−0.37	−1.11	−2.23	0.50	−0.25	−1.36
1950–1960	3.76	4.09	4.59	3.75	4.08	4.58
1960–1970	3.35	3.62	4.04	3.25	3.52	3.94
1970–1980	3.56	3.26	2.81	4.25	3.95	3.50
1980–1990	3.99	4.60	5.51	4.05	4.65	5.56
1990–1996 (Cen-CPS)	2.75	2.91	3.15	1.98	2.14	2.38
1990–1996 (CPS-CPS)	2.33	2.49	2.73	2.81	2.97	3.21

C. Changes in relative wage, supply, and demand ($\sigma = 1.4$) for aggregated time periods

		College graduates		College equivalents	
	Relative wage	Relative supply change	Relative demand change	Relative supply change	Relative demand change
1940–1970	−0.11	2.36	2.20	2.61	2.45
1970–1996	0.39	3.06	3.60	3.45	3.99
1950–1980	0.26	3.29	3.66	3.49	3.85
1940–1960	−0.51	2.21	1.74	2.63	1.92
1960–1980	−0.02	3.48	3.44	3.77	3.74
1980–1996	1.10	2.28	3.81	2.49	4.02

σ is the aggregate elasticity of substitution between college or college equivalent and noncollege workers.

Wage-bill shares, defined as the share of total weekly wages paid to each education group, are calculated from the samples described in the notes to Table I. College equivalents are defined as those with a college education plus half of those with some college. Noncollege (or high school) equivalents are those with twelve or fewer years of schooling (or high school diploma or less) plus half of those with some college. In CPS samples, hourly wages for the self-employed are imputed using average weekly wages for wage and salary workers in the same industry-education-year cell. Annual log wage changes for the 1990–1996 period reported in the first column of panel A are based on the college-plus/high school differentials estimated from the February 1990 CPS and 1996 CPS MORG samples. The relative supply changes tabulated in the third and fifth columns of panel A and the second and fourth columns of panel C are the difference between the change in the relative wage bill and the change in relative college-plus/high school wages. See the Data Appendix for details.

in product demand among industries with different skill intensities.

Under the assumption that the economy operates on its labor demand curve so that college and high school equivalents are paid their marginal products, we can use (1) to solve for the ratio of marginal products of the two labor types, yielding a relationship between relative wages (w_{ct}/w_{ht}) and relative supplies (N_{ct}/N_{ht}) given by

$$\log (w_{ct}/w_{ht}) = (1/\sigma)[D_t - \log (N_{ct}/N_{ht})], \tag{2}$$

where D_t indexes relative demand shifts favoring college equivalents and is measured in log quantity units.[10] The impact of changes in relative skill supplies on relative wages depends inversely on the magnitude of aggregate elasticity of substitution between the two skill groups. Changes in D_t can arise from pure skill-biased technological change, nonneutral changes in the relative prices or quantities of nonlabor inputs such as computer services, increased outsourcing possibilities that disproportionately affect the two skill groups, and shifts in product demand from either domestic or international sources.[11]

Solving equation (2) for D_t and rearranging terms yields

$$D_t = \log ([w_{ct}N_{ct}]/[w_{ht}N_{ht}]) + (\sigma - 1) \log (w_{ct}/w_{ht}). \tag{3}$$

Equation (3) implies that changes in the log relative demand for college equivalents equals the sum of the change in the log relative wage bill and a term that depends positively (negatively) on the change in the log college wage premium when $\sigma > 1$ ($\sigma < 1$). If $\sigma = 1$, then changes in the log relative demand for college equivalents are directly given by changes in the log relative wage bill of college workers.

Under a plausible assumed value for σ, we can use (3) and data on the time series of relative wages and quantities to impute the time pattern of relative demand shifts. Katz and Murphy [1992] find a point estimate of $\sigma = 1.41$ using U. S. annual time series information on the college wage premium and relative

10. $D_t = \sigma \log (\alpha_t/[1 - \alpha_t]) + (\sigma - 1) \log (a_t/b_t)$.

11. Thus, our approach is consistent with the possibility of capital-skill complementarity. In fact, the nested CES aggregate production function explicitly allowing for capital-skill complementarity used by Krusell et al. [1997] yields a relative wage determination equation that can be written in the same form as equation (2). In this case D_t includes a term that depends on the ratio of capital equipment to skilled labor as well as a term reflecting other forms of skill-biased technological change.

quantities of college and high school equivalents derived from the March CPSs for the 1963–1987 period. Other recent studies using U. S. data from the early 1960s to the early 1990s yield estimates of the aggregate elasticity of substitution between college and noncollege workers from 1.3 to 1.7 [Heckman, Lochner, and Taber 1998; Krusell et al., 1997]. Although substantial uncertainty exists concerning the magnitude of σ, recent empirical estimates suggest that σ is likely to be between 1 and 2, with an emerging consensus "best guess" estimate of approximately 1.4 to 1.5 [Johnson 1997].

Panel A of Table II presents changes by decade in the log college wage premium as well as changes in the college/noncollege log relative wage bill and (composition-adjusted) supply using both the college graduate and college equivalents aggregation schemes. The (composition-adjusted) log relative supply change is given by the log relative wage-bill change minus the log relative wage change. The 1970s is the outlier decade in terms of relative supply growth. The rate of growth of the log relative supply of college workers accelerates dramatically in the 1970s and then decelerates substantially in the 1980s and 1990s under either classification scheme.[12]

The sensitivity of conclusions concerning the time path of the growth of the relative demand for college workers to assumptions about the magnitude of σ and the approach to defining skill groups is illustrated in Panel B of Table II.[13] Panel C of Table II compares changes in the growth of the college relative wage, supply, and implied demand (assuming that $\sigma = 1.4$) for selected aggregated time periods. The base case assumption of $\sigma = 1.4$ implies that the sharp difference in the behavior of the college

12. The time pattern of relative supply growth is quite similar if one directly adjusts for compositional changes in the college and noncollege groups by measuring employment in efficiency units in which hours worked are weighted by the average hourly wage of each individual's demographic group (e.g., age-sex-education group) in a base year (such as 1980).

13. The implied relative demand shifts are computed by plugging the data on changes in log relative wages and wage bills from panel A into equation (3). Johnson [1997] presents a related analysis of implied relative demand shifts for college equivalents from 1940 to 1993 under the assumption of $\sigma = 1.5$. Johnson's findings are quite similar to our results for college equivalents with $\sigma = 1.4$ except for the 1990s. Johnson's estimate of the growth of the college wage premium in the 1990s is unusually high relative to other estimates (e.g., Mishel, Bernstein, and Schmitt [1997a, 1997b]), and his estimate of the growth of the relative supply of college equivalents in the 1990s does not appear to adjust for the substantial changes in education coding in the CPS over this period. Thus, Johnson's rather large estimate of relative demand growth in the early 1990s appears to be upward biased.

relative wage in the 1970s and 1980s can be attributed to both slower relative supply growth and faster relative demand growth in the 1980s. A comparison of the period of large increase in the college wage premium from 1980–1996 with the period of little change from 1960–1980 suggests that a deceleration in relative supply growth is more important than an acceleration in relative demand growth in explaining the recent expansion of educational wage differentials. A marked decrease in the rate of growth of relative demand is apparent in the 1990s, and the compression of educational wage differentials in the 1940s is attributed to slow (and possibly negative) relative demand growth for college workers.[14]

Overall, Table II implies that strong secular relative demand growth for college workers since 1950 is necessary to reconcile the large increases in the college wage premium in the face of large relative skill supply increases. The data do not lead to an unambiguous answer to the question of whether the trend rate of demand growth has increased recently. Under our preferred estimate of $\sigma = 1.4$, we find that the growth in the relative demand for college equivalents is rather steady from 1950 to 1980, unusually fast in the 1980s, and rather slow in the 1990s. The hypothesis of an acceleration in relative demand growth in the 1980s is supported by assuming that σ is in the range of recent estimates (1.3 to 1.7). But the slowdown in demand growth in the 1990s is surprising given the continuing spread of computers and large growth of U. S. trade with less-developed countries in the 1990s [Borjas, Freeman, and Katz 1997].

Panel C of Table II does indicate that the average rate of growth of relative demand for college workers was more rapid during the past 26 years (1970–1996) than during the previous 30 years (1940–1970). This pattern is suggestive of an increased rate of skill-biased technological progress starting in the early 1970s as has been hypothesized by Greenwood and Yorukoglu [1997]. This conclusion is dependent on including the 1940s, a decade of strong institutional intervention in the labor market, in the earlier period. Furthermore, the decadal comparisons in panel B of Table II as well as annual time series data from the March CPSs

14. But much evidence suggests the wage compression in the 1940s was at least partially driven by institutional factors including direct government intervention in wage setting during World War II, the rapid expansion of unions, and possible changes in previous customary wage-setting norms [Goldin and Margo 1992].

[Katz and Murphy 1992; Krusell et al. 1997; Murphy, Riddell, and Romer 1998] do not indicate a discrete trend break in demand growth for the more-skilled in the 1970s.

B. Shift-Share Analysis

What factors explain the rapid secular shift of relative labor demand favoring more-educated workers and the variation in the pace of demand shifts across decades? Explanations based on increased trade or "deindustrialization" are likely to involve shifts in the derived demand for labor between industries from those intensive in less-skilled workers (such as less-educated, import-competing sectors) to those intensive in more-skilled workers (such as more-educated, exporting sectors). Broad skill-biased technological change and changes in the organization of work that favor more-skilled workers could operate by reducing the relative demand for less-educated workers within detailed industries. Alternatively, the growth of the foreign outsourcing of low-skill tasks could also generate substantial within-industry increases in the relative utilization of more-educated workers.

A decomposition of the growth of the share of aggregate employment (or of the aggregate wage bill) accounted for by college graduates into between- and within-industry components can help illustrate the potential importance of these alternative channels [Berman, Bound, and Griliches 1994]. A standard decomposition of the change in the proportion of group j (college graduates) in aggregate employment between years τ and t ($\Delta P_{jt} = P_{jt} - P_{j\tau}$) into a term reflecting the reallocation of labor across sectors and a term reflecting changes in the college graduate share of employment within industries is given by

$$\Delta P_{jt} = \sum_k (\Delta E_{kt}\gamma_{jk.}) + \sum_k (\Delta\gamma_{jkt}E_{k.}) = \Delta P^b_{jt} + \Delta P^w_{jt}, \tag{4}$$

where k indexes industries, E_{jkt} is the employment of group j in industry k in year t as a share of aggregate employment in year t, $E_{kt} = \Sigma_j E_{jkt}$ is total employment in industry k in year t, $\gamma_{jkt} = E_{jkt}/E_{kt}$ is the group j share of employment in industry k in year t, $\gamma_{jk.} = (\gamma_{jkt} + \gamma_{jk\tau})/2$, and $E_{k.} = (E_{kt} + E_{k\tau})/2$. The first term ($\Delta P^b_{jt}$) reflects the change in the aggregate proportion of college graduates attributable to changes in employment shares *between* industries that utilize different proportions of college graduates. The second term (ΔP_{jt}^{w}) reflects *within-industry* skill upgrading. An analogous decomposition can be performed to analyze changes in the aggregate wage-bill share of college graduates.

Table III presents between- and within-industry decomposi-

TABLE III
BETWEEN- AND WITHIN-INDUSTRY DECOMPOSITION OF THE INCREASE IN THE SHARE OF COLLEGE GRADUATES IN EMPLOYMENT, 1960–1996, DEPENDENT VARIABLE IS 100× (ANNUAL CHANGE IN COLLEGE GRADUATE EMPLOYMENT AND WAGE-BILL SHARE)

A. Employment

	All industries			*Manufacturing*			*Nonmanufacturing*		
	Between	Within	Total	Between	Within	Total	Between	Within	Total
1960–1970 Census-Census	.237	.087	.324	.044	.121	.166	.287	.074	.361
1970–1980 Census-Census	.122	.464	.586	.024	.375	.399	.115	.494	.609
1980–1990 CPS-CPS	.098	.371	.469	.064	.441	.505	.055	.353	.408
1990–1996 Census-CPS	−.042	.505	.463	−.063	.594	.531	−.063	.487	.423
1990–1996 CPS-CPS	.039	.261	.300	−.087	.309	.222	.034	.251	.285

B. Wage bill

	All industries			*Manufacturing*			*Nonmanufacturing*		
	Between	Within	Total	Between	Within	Total	Between	Within	Total
1960–1970 Census-Census	.278	.232	.511	.068	.273	.342	.320	.214	.534
1970–1980 Census-Census	.107	.555	.662	.026	.471	.497	.094	.586	.680
1980–1990 CPS-CPS	.266	.612	.878	.163	.745	.908	.224	.573	.797
1990–1996 Census-CPS	.051	.601	.652	−.020	.909	.889	.035	.527	.562
1990–1996 CPS-CPS	.083	.484	.567	−.117	.569	.452	.092	.463	.555

1960–1970 and 1970–1980 changes use data from the 1960, 1970, and 1980 Census PUMS. 1980–1990 changes use data from the CPS Merged Outgoing Rotation Group files. 1990–1996 Census-CPS changes use the 1990 Census PUMS and the 1996 CPS Merged Outgoing Rotation Groups. 1990–1996 CPS-CPS changes use the February 1990 CPS and the 1996 CPS Merged Outgoing Rotation Groups. Decompositions are based on the 140 consistent CICs described in the Data Appendix (59 in manufacturing, 81 in nonmanufacturing). Employment and wage-bill shares are based on all currently employed wage and salary and self-employed workers in the Census and CPS at the survey dates. Hourly wages are imputed for the self-employed in each sample using the average hourly wage for wage and salary workers in the same industry-education cell. Hours are imputed for the self-employed in the CPS in the same manner, using average hours and wages of wage and salary workers in the same industry-education cells.

tions of both the growth in the share of employment and of the wage bill accounted for by college graduates from 1960 to 1996 using 140 three-digit industries (made consistent among 1960, 1970, 1980, and 1990 Census Industry Codes). The between-industry components of the change in the college wage bill and employment share are greatest in the 1960s mainly as a result of the rapid growth of the college-intensive education and public administration sectors. The decline in the between-industry component in manufacturing in the 1990s appears related to substantial declines in employment of education-intensive industries greatly affected by defense downsizing. The vast majority of the secular growth in the utilization of college graduates can be attributed to within-industry changes.[15]

An acceleration in the growth of the employment and wage-bill shares of college graduates in the 1970s and 1980s relative to the 1960s is driven by within-industry increases. The rate of within-industry skill upgrading remains high in the 1990s. In fact, the within-industry growth in the college wage-bill share (as well as the college employment share) is faster in the 1970s, 1980s, and 1990s than in the 1960s in both manufacturing and nonmanufacturing.[16] Thus, the pace of within-industry skill upgrading appears to have increased starting in the 1970s, but the precise time pattern is somewhat different in the manufacturing and nonmanufacturing sectors. A large increase in the within-industry growth of the college wage-bill share occurs from the 1960s to the 1970s outside of manufacturing. A further sharp increase from the 1970s to the 1980s is apparent in manufacturing.

Under some strong assumptions, we can use the shift-share decomposition of the growth of the college wage-bill share to more directly measure the extent to which the growth in the relative demand for college workers reflects skill-biased technological change as opposed to product demand shifts across industries with different skill-intensities. Following Bound and Johnson [1992], we assume output of each industry $k(Q_k)$ depends on the

15. Since we examine employment by three-digit industries, our within-industry component could mask potentially significant between-industry shifts for more disaggregated industries. But Dunne, Haltiwanger, and Troske [1996] find with plant-level data for manufacturing that aggregate changes in skilled labor (nonproduction worker) employment and labor cost shares are dominated by within-plant changes.

16. Berman, Bound, and Griliches [1994] reach a similar conclusion for the time pattern of within-industry growth of the nonproduction worker wage bill in manufacturing from 1959 to 1989.

employment of college and high school equivalents according to a CES production function of the form of equation (1) with a common elasticity of substitution ($\sigma = 1/(1 - \rho)$) but with the other technology parameters (α_{kt},a_{kt}, and b_{kt}) varying by industry and time. The relative demand for the output of industry k relative to a reference industry r in period t is assumed to be given by

$$Q_{kt}/Q_{rt} = \theta_{kt}(P_{kt})^{-\epsilon}, \tag{5}$$

where P_{kt} is the price of Q_{kt} relative to Q_{rt} and θ_{kt} is a parameter that reflects consumer tastes and other factors (such as foreign competition) affecting relative product demand for the output of industry k in year t. Katz and Autor [1998] show in the special case of a Cobb-Douglas economy ($\sigma = \epsilon = 1$) that aggregate log relative demand for college workers (D_t) is given by the log relative wage bill of college workers (as in equation (3) with $\sigma = 1$) and can be decomposed into a between-industry component that depends only on product demand shifts (changes in the θ_{kt}'s) and a within-industry component that depends only on the pace of skill-biased technological change (changes in the α_{kt}'s).[17]

Under these Cobb-Douglas assumptions the change in the within-industry component of the log relative demand for college graduates measures the impact of skill-biased technological change on relative demand growth and can be directly calculated from the within-industry component of the shift share decomposition of the college wage-bill share given in panel B of Table III. This approach implies that the annual percentage change (100 times the annual log change) in the within-industry component of the relative demand for college graduates (for all industries) is 1.60 in the 1960s, 2.98 in the 1970s, 2.84 in the 1980s, and 2.51 from 1990 to 1996 (using Census data for 1990 and CPS data for 1996).[18] Thus, the rate of within-industry relative demand growth for college graduates appears to have increased from the 1960s to the 1970s

17. Product market shifts may also occur within three-digit industries leading to shifts in production across firms with different skill intensities and possible within-firm changes in product and skill mixes.

18. These estimates are based on combining the within-industry component of college wage-bill share growth for all industries presented in panel B of Table III with information in panel B of Appendix 1 on the level of college wage-bill share at the start of each period. Let Y_c and Y_h equal the aggregate wage-bill shares for college graduates and noncollege workers. If $\sigma = 1$, then equation (3) implies that the change in the log relative demand for college workers ($\Delta D_t = D_t - D_\tau$) can be written as

$$\Delta D_t = \Delta \log (Y_{ct}/Y_{ht}) = \log (1 + [\Delta Y_{ct}/Y_{c\tau}]) - \log (1 + [\Delta Y_{h\tau}/Y_{h\tau}]).$$

and remained at a higher level in the 1980s and 1990s. This restrictive Cobb-Douglas framework suggests a larger impact of skill-biased technological change on the growth in the relative demand for college workers from 1970 to 1996 than in the 1960s.[19]

In summary, rapid relative demand growth favoring more-skilled workers is apparent throughout the 1950 to 1996 period. Changes in relative demand occurring within (three-digit) industries dominate the growth in relative demand for college workers over the past three decades. Although the evidence is somewhat ambiguous concerning whether the trend rate of growth in the overall relative demand for college workers has increased in recent decades, the pace of within-industry relative demand growth appears to have increased starting in the 1970s.

III. Trends in Computer Technology

The diffusion of computers and related technologies is a possibly important measurable source of changes in the relative demand for skills which has been operating for at least several decades. Computer technology may influence relative labor demand in several ways.[20] Computer business systems often involve the routinization of many white-collar tasks. Simple, repetitive

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Katz and Autor [1998] show that the within-industry component of log relative demand growth is given by

$$\Delta D_t^w = \log\left(1 + [\Delta Y_{ct}^w / Y_{c\tau}]\right) - \log\left(1 + [\Delta Y_{ht}^w / Y_{h\tau}]\right),$$

where $\Delta Y_{ct}^w = -\Delta Y_{ht}^w$ = the within-industry component of college wage-bill share growth given by a modified version of equation (4) with the wage bill replacing employment.

19. If we drop the Cobb-Douglas assumption of $\sigma = \epsilon = 1$, then a decomposition of demand shifts into between- and within-industry components no longer cleanly separates out the effects of product demand shifts and technological change on relative labor demand. But, more generally, the aggregate elasticity of substitution between college and noncollege labor equals the industry-level elasticity of substitution when $\sigma = \epsilon$ [Johnson and Stafford 1998]. Then under our preferred estimate of $\sigma = 1.4$, we can adjust the within-industry component of log college relative wage-bill growth for changes in relative wages using equation (3) to generate an estimate of the within-industry component of the growth in log relative demand. In this case the annual percentage change in the within-industry component of the relative demand for college graduates is 1.88 in the 1960s, 2.68 in the 1970s, 3.44 in the 1980s, and 2.67 from 1990 to 1996. Thus, this scenario leads to a similar conclusions to the Cobb-Douglas case concerning an increased rate of within-industry relative demand growth starting in the 1970s.

20. Bresnahan [1997] provides a descriptive theory of and illuminating historical evidence on how computers affect labor demand and organizational practices. Levy and Murnane [1996] examine a case study of this process in the financial services industry.

tasks have proved more amenable to computerization than more complex and idiosyncratic tasks [Bresnahan 1997]. Microprocessor-based technologies have similarly facilitated the automation of many production processes in recent years. Thus, direct substitution of computers for human judgment and labor is likely to have been more important in clerical and production jobs than in managerial and professional jobs. Computer-based technologies may also increase the returns to creative use of greater available information to more closely tailor products and services to customers' specific needs and to develop new products. Bresnahan [1997] posits such an organizational complementarity between computers and workers who possess both greater cognitive skills and greater "people" or "soft" skills. The direct substitution and organizational complementarity channels both predict that an increase in the relative demand for highly educated workers should be associated with computerization.

Bresnahan, Brynjolfsson, and Hitt [1998] find in firm-level data that greater use of information technology is associated with the employment of more-educated workers, greater investments in training, broader job responsibilities for line workers, and more decentralized decision-making. They hypothesize that advances in information technology are complementary with organizational changes to improve service quality through the use of skilled workers with substantial individual autonomy. Their survey of human resource managers indicates that a majority of these managers believe computerization increases skill requirements and worker autonomy but also increases management's ability to monitor workers. Our interpretation is somewhat similar. We do not view the spread of computers as simply increasing the demand for computer users and technicians, but more broadly as a part of a technological change that has altered the organization of work and thereby more generally affected the demand for workers with various skills. The computer revolution may thereby be an important component of secular increases in the relative demand for skilled worker in recent decades.

Although computer technology dates back to at least the 1940s, microprocessors first were introduced on a wide scale in manufacturing machinery in the 1970s. Bresnahan [1997] notes that mainframe computers started to be extensively used in business (especially in financial services) in the late 1950s and early 1960s. The diffusion of organizational applications of computers accelerated in the 1960s and 1970s and continues at a rapid rate to the present day. With the birth of the Apple II in 1977 and the IBM PC in 1981, personal computers (PC's) spread rapidly in the 1980s and early 1990s. The historical pattern of the spread of computers suggests that computerization is likely to have affected relative skill demands in the service sector prior to its major impacts in manufacturing. This prediction appears consistent with the findings presented in Table III of a more rapid increase in within-industry skill upgrading outside of manufacturing from the 1960s to the 1970s and in the manufacturing sector from the 1970s to the 1980s.

We begin our analysis of computerization with one admittedly incomplete measure of the spread of computer technology: the fraction of workers who directly use a computer keyboard. Although this measure misses workers who use devices with embedded microprocessors not operated by keyboards, it does reflect a particularly prevalent form of computer technology. Table IV reports the percentage of workers who report using a computer keyboard at work in selected years. The table is based on data from the CPS for October 1984, 1989, and 1993. The prevalence of computer use at work increased almost linearly from one-quarter of the workforce in 1984, to over one-third in 1989, and to nearly one-half in 1993—an average increase of 2.4 percent of the workforce per year. Unfortunately, comparable data are not available for earlier years.

The growth in computer use since 1984 has not been uniform across demographic groups. Table IV shows that women, more highly educated workers, whites, white-color workers, and full-time workers are more likely to use computers. The groups that experienced the greatest increases in computer use between 1984 and 1993 are also more likely to have experienced relative wage gains. Furthermore, Krueger [1993] and Autor, Katz, and Krueger [1997] document a substantial log wage premium associated with computer use (conditional on standard controls for observed worker characteristics) that increased from 0.17 in 1984 to 0.20 in 1993.[21]

Computer use and its growth also varies substantially across

21. Whether the computer wage premium represents a measure of the true returns to computer skills or largely reflects omitted characteristics of workers and their employers is currently the subject of debate (see, for example, Bell [1996] and DiNardo and Pischke [1997]).

TABLE IV
PERCENT OF WORKERS IN VARIOUS CATEGORIES WHO DIRECTLY USE A COMPUTER AT WORK

	October 1984	October 1989	October 1993
Use a computer			
All workers	25.1	37.4	46.6
Gender			
Male	21.6	32.2	41.1
Female	29.6	43.8	53.2
Education			
Less than HS	5.1	7.7	10.4
High school	19.2	28.4	34.6
Some college	30.6	45.0	53.1
College+	42.1	58.5	70.2
Race			
White	25.8	38.5	48.0
Black	18.6	28.1	36.7
Age			
Age 18–24	20.5	29.6	34.3
Age 25–39	29.6	41.4	49.8
Age 40–54	23.9	38.9	50.0
Age 55–64	17.7	27.0	37.3
Occupation			
Blue-collar	7.1	11.2	17.1
White-collar	39.7	56.6	67.6
Union member			
Yes	19.9	31.8	39.1
No	25.3	37.7	46.9
Hours			
Part-time	14.8	24.4	29.3
Full-time	29.3	42.3	51.0
Region			
Northeast	25.5	37.6	46.9
Midwest	24.3	36.6	46.7
South	23.2	36.6	45.0
West	28.9	39.7	48.8

Data are from the October 1984, 1989, and 1993 Current Population Surveys. Sample sizes are 61,704, 62,748, and 59,852 in 1984, 1989, and 1993, respectively. Estimates are weighted by CPS sample weights. Sample includes workers ages 18–64 who were working or who had a job but were not at work in previous week.

industries.[22] It has become especially prevalent in such industries as legal services, dairy products, advertising, and public administration, while remaining unsurprisingly rare in logging, taxicab services, and bowling alleys. We next focus on cross-industry data

22. Appendix Table A2 of Autor, Katz, and Krueger [1997] reports the extent of computer use in 1984, and growth in computer use between 1984 and 1993, for 140 (approximate three-digit) industry groups.

to examine whether the spread of computers is associated with increases in the relative utilization of highly educated labor.

IV. Evidence on Computers and Interindustry Skill Upgrading

Most of the rise in the employment and wage-bill shares of college graduates since 1970 has occurred within detailed industries. To better understand the determinants of within-industry shifts toward more highly educated workers, we relate the change in the share of workers in each educational group across industries to industry-level measures of computer utilization. One interpretation of such a relationship is that the exogenous driving force is the rapid decline in the relative price of information technology. Industries vary in their ability to reorganize work to take advantage of computer technologies. In this case, cross-industry correlations of measures of computer use with changes in the relative employment of different skill groups may provide information about the extent of the relative complementarity or substitutability of these skill groups with computer technologies.

Table V presents initial results for the 1979–1993 period. The dependent variable is the annual change in the fraction of workers employed in each education group between 1979 and 1993, calculated from the MORG files of the CPS. The explanatory variable of interest is the annual change in the fraction of workers in the industry who used a computer, calculated from the 1984 and 1993 October CPSs. The results indicate that the shift toward college-educated workers, and away from high school-educated workers, was greatest in industries that experienced the greatest rise in computer use.

This association between the rise in the proportion of workers in an industry who use a computer and the share of highly educated workers may not represent a causal relationship. It is possible, for example, that an exogenous increase in employment of college graduates causes the industry to adopt computers, rather than vice versa. We explore the issue of causality further in the next section.

The magnitude of the coefficient on the fraction of workers using a computer, if it represents a causal effect of technology, implies that the growth of computers at work can account for a large share of the growth of college-educated employment. Between 1979 and 1993, college-educated workers' share of employment increased by 0.36 percentage points per year. The intercept

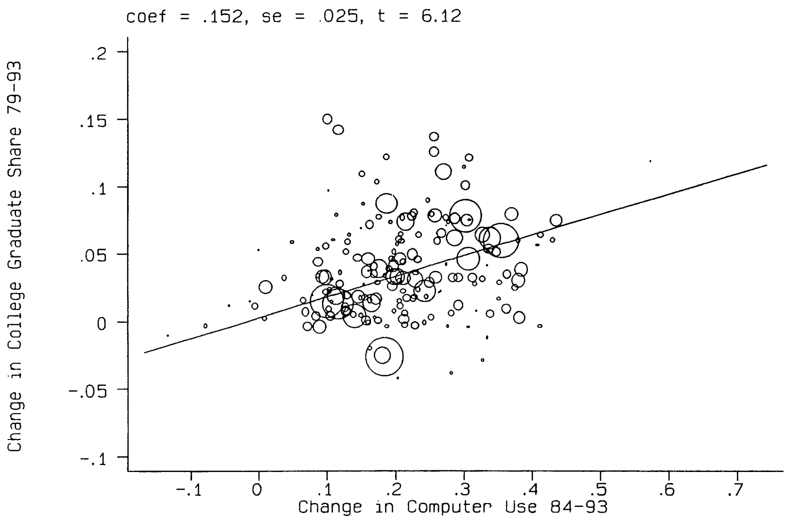
TABLE V
OLS FIRST-DIFFERENCE ESTIMATES OF THE RELATIONSHIP BETWEEN COMPUTERIZATION AND EDUCATIONAL UPGRADING IN THREE-DIGIT INDUSTRIES BETWEEN 1979 AND 1993, DEPENDENT VARIABLE IS 100× (ANNUAL CHANGE IN EMPLOYMENT SHARE)

	(1)				(2)			
	College	Some college	HS grad	Less than HS	College	Some college	HS grad	Less than HS
ΔComputer use 1984–1993	.152	.016	−.301	.133	.190	.060	−.251	.001
	(0.025)	(0.020)	(0.034)	(0.026)	(0.029)	(0.024)	(0.040)	(0.025)
Mean ed 1974					−.005	−.006	−.006	.017
					(0.002)	(0.002)	(0.003)	(0.002)
Intercept	.028	.612	.223	−.863	.549	1.228	.911	−2.687
	(0.059)	(0.048)	(0.079)	(0.060)	(0.229)	(0.185)	(0.309)	(0.194)
R^2	.166	.003	.299	.126	.190	.063	.319	.420
n	191	191	191	191	190	190	190	190
Weighted mean change	.357	.646	−.427	−.576	.357	.646	−.427	−.576

Standard errors are in parentheses. Δ Computer use is ten times the change in industry computer use frequency between 1984 and 1993 as reported in the October 1984 and 1993 CPS. Change in educational shares are measured as 100 times the annual change in the share of industry workers in each educational category as reported in the 1979 and 1993 Merged Outgoing Rotation Groups of the CPS. Lagged industry education means are drawn from the May 1974 CPS and are multiplied by ten. Industries are coded as 191 consistent CICs, spanning the standard 1970, 1980, and 1990 CICs. All regressions are weighted by the product over the sum of the industry's share of total employment in each of the two years used in constructing the dependent variable. See the Data Appendix for details.

of the bivariate regression in the first column of Table V, however, is just 0.03, which implies that at a constant level of computer use one would predict hardly any increase in the share of college-educated employment over this period. More rapid growth of computer use is also negatively related to the change in the share of those with exactly high school degrees in industry employment. The contrasting relations of change in computer use from 1984 to 1993 with changes in the employment shares of college and high school graduates from 1979 to 1993 are illustrated in Figure I parts (a) and (b). Clearly the regressions in Table V are not driven by a few outlier industries.

Surprisingly, Table V indicates that faster growth in computer use is associated with a relative rise in the share of less-than-high school workers in an industry. This finding results in large part because industries that saw the greatest growth in computer use employed relatively few high school dropouts initially, and employment of high school dropouts fell substantially *(a) College Graduates*



(b) High School Graduates

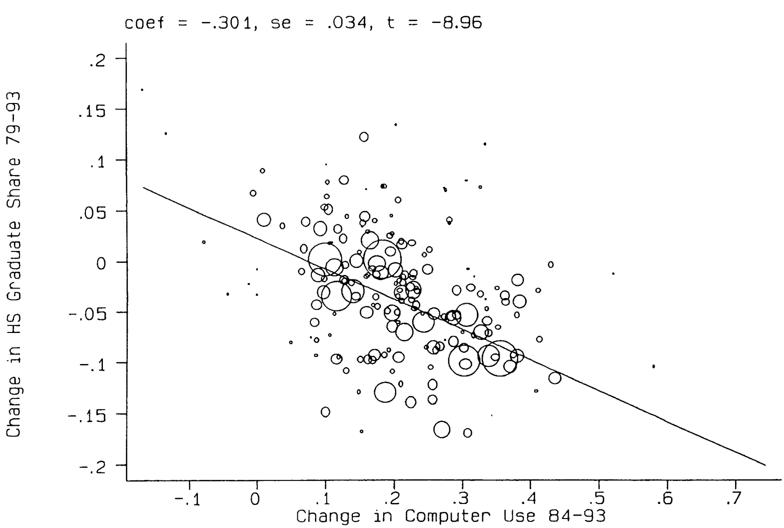


FIGURE I
Changes in Computer Use and Industry Workforce Educational Shares

in almost all industries during this period. There is a limit to how much the share of high-school dropouts can fall in high-tech industries that initially employed very few high school dropouts. When the average years of education in an industry (measured in 1974 to avoid a mechanical correlation) is controlled in the right-hand part of Table V, the growth of computer use across industries has an insignificant effect on the employment share of less-than-high school workers, but continues to have a strong positive effect on employment of college graduates and a strong negative effect on employment of high school graduates.

Four robustness checks are worth reporting. First, similar results are obtained if each educational group's share of hours or of payroll is used as the dependent variable. Second, comparable results are found if the models in Table V are estimated for separate samples of men and women. Third, the growth in computer use is not perfectly aligned with the dependent variable in Table V because data on the fraction of workers who use a computer are not available prior to 1984. If the dependent variable is based on the 1984–1993 change in employment shares, however, the results are qualitatively similar.

Finally, to examine the results for another measure of employee skill, we have performed an analogous analysis using industry-level data to relate the annualized change in the proportion of workers in each *major occupational category* between 1979 and 1993 to the annualized change in the fraction of workers in the industry who use a computer. Consistent with the educational upgrading patterns, these results indicate that industries that experienced the greatest growth in computer use tended to shift their occupational mix toward managers and professionals, and away from administrative support/clerical and service workers. In general, occupations with higher average pay and higher education tended to expand more rapidly in sectors that adopted computer technology at a faster rate.

V. Computer Use and the Timing of Skill Upgrading

A concern with the regressions in Table V is that they may reflect past trends in skill upgrading, rather than a discrete break from preexisting trends. Furthermore, causality could be reversed—hiring more educated workers may lead an industry to subsequently adopt computer technology.[23] To provide a partial check on these possibilities, we use Census and CPS data to look at the relationship between employment shifts in each decade since 1960 and recent changes in computer use.

If the post-1979 shift toward more highly educated workers in industries that expanded computer use reflects a continuation of earlier trends in skill upgrading, then we would expect to see a similar pattern of employment shifts in the 1960s, prior to the spread of PC's at work. Specifically, consider the following variance components model for the change in the wage-bill share of college graduates across industries:

$$\Delta WB_{it} = \delta_t + \beta_i + \epsilon_{it}, \tag{6}$$

where ΔWB_{it} represents the change in the wage-bill share of college graduates in industry i and period t (corresponding to the 1960s, 1970s, 1980s, or 1990s), β_i represents a time-invariant skill bias factor for industry i, δ_t is a time effect, and ϵ_{it} is an error term. If β_i is positively correlated with the change in computer use between 1984 and 1993, then the estimated effect of computer growth in Table V will at least partially reflect the preexisting industry fixed effect, rather than an acceleration in skill upgrading in response to new computer technology.

An alternative hypothesis is that industries that increase computer usage experience an "acceleration" in the rate of skill upgrading. Since we lack direct information on employee computer usage prior to 1984, this hypothesis suggests estimating the following simple regression model for different time periods:

$$\Delta WB_{it} = \delta'_t + \lambda_t \Delta C_i + \epsilon'_{it}, \tag{7}$$

where ΔC_i is the change in the proportion of workers using a computer in industry i between 1984 and 1993 and λ_t is a time-varying parameter. If the results in Table V simply reflect stable preexisting trends, then the estimates of λ_t ought to be similar for the 1960s, 1970s, 1980s, and the 1990s. If recent increases in computer use reflect an acceleration of the skill-biased technological change, then the estimates of λ_t should be higher for more recent decades.

23. Doms, Dunne, and Troske [1997] find that manufacturing plants that employ more-educated workers are more likely to adopt new factory automation technologies, but they find little correlation between the adoption of such technologies and subsequent skill upgrading. Nevertheless, Doms, Dunne, and Troske do find a strong positive correlation of computer investments as a share of total investment and skill upgrading at the plant level.

TABLE VI
OLS FIRST-DIFFERENCE ESTIMATES OF THE RELATIONSHIP BETWEEN COMPUTERIZATION 1984–1993 AND GROWTH IN THE COLLEGE WAGE-BILL SHARE IN THREE-DIGIT INDUSTRIES 1960–1996 DEPENDENT VARIABLE IS 100× (ANNUAL CHANGE IN COLLEGE WAGE-BILL SHARE)

	Intercept	Δ Computer use 1984–1993	R^2	Weighted mean of dependent variable
1960–1970 (Census-Census)	.085	.071	.053	.233
	(.058)	(.025)		
1970–1980 (Census-Census)	.279	.127	.107	.554
	(.073)	(.031)		
1980–1990 (CPS-CPS)	.287	.147	.070	.614
	(.108)	(.046)		
1990–1996 (CPS-CPS)	−.171	.289	.080	.485
	(.196)	(.081)		

Standard errors are in parentheses. All models contain 140 observations. Computer use is measured as ten times the change in industry computer use frequency between 1984 and 1993 as reported in the October 1984 and 1993 CPS. College wage-bill shares are measured as the industry wage-bill share of workers with sixteen-plus completed years of schooling and as the industry wage-bill share of workers holding at least a B.A. in 1990–1996 changes. 1960–1970 and 1970–1980 changes use data from the 1960, 1970, and 1980 Census PUMS. 1980 to 1990 changes use data from the 1980 and 1990 CPS Merged Outgoing Rotation Group files. 1990–1996 changes use data from the February 1990 CPS and the 1996 CPS Merged Outgoing Rotation Groups. Industries are coded as 140 consistent CICs, spanning the standard 1960, 1970, 1980, and 1990 CICs. All regressions are weighted by the product over the sum of the industry share of the total wage bill in each of the two years used in constructing the dependent variable. See the Data Appendix for details.

Table VI reports estimates of equation (7); that is, bivariate regressions of the annual change in the *share of payroll* due to college-educated workers in selected periods on the 1984–1993 change in the fraction of workers in the industry who use a computer.[24] An industry's 1984–1993 increase in computer utilization has a somewhat weaker relationship with the change in the wage-bill share of college-educated workers in the 1960s than it does in the later decades. The coefficient on the computer adoption variable is modestly higher in the 1970s and 1980s than in the 1960s, but substantially greater in the 1990–1996 period. These findings suggest that the pace of skill upgrading in industries that

24. In the remainder of this study, we focus on changes in the college wage-bill share as our primary measure of within-industry skill upgrading, both for comparability with the specifications used in previous work (e.g., Berman, Bound, and Griliches [1994]) and because, as equation (3) illustrates, the change in an industry's relative wage-bill share of college workers is a close proxy for the growth in its relative demand for college workers if the elasticity of substitution between college and noncollege workers at the industry level is close to one. The findings are generally quite similar if we use changes in the payroll share of college equivalents or in the employment share of college graduates or college equivalents as the dependent variable.

more rapidly adopted computer technology in the 1984–1993 period increased relative to other industries after the 1960s. But the models estimated in Table VI are limited because they do not include data on indicators of industry computer intensity before 1984 or on other controls for overall capital intensity.

VI. Computers, Capital Intensity, R&D, and Skill Upgrading

We next examine whether the positive relation between the growth in computer usage and skill upgrading reflects factors specific to computers, or broader patterns of capital-skill complementarity. To perform such an exercise, one must combine data on the educational attainment of industry workforces with data on the magnitude and composition of each industry's physical capital stock and capital investments. As described in the Data Appendix, we link data on educational shares of industry employment and wage bills from our Census and CPS samples with National Income and Product Accounts (NIPA) data on industry capital stocks, investment, and full-time equivalent employees (FTEs). Data from the CPS and Census are matched to NIPA data in 47 aggregated (approximate two-digit) industries covering all private industry sectors (except for private household services).

The NIPA data provide information on overall capital intensity and several potential measures of "high-tech" capital intensity. The closest measure to our CPS measure of computer utilization is the stock of office computing and accounting machinery (OCAM) per worker.[25] Berndt, Morrison, and Rosenblum [1992] define a broader measure of high-tech capital as the sum of the real net stocks of OCAM, scientific and engineering equipment, communications equipment, and photocopy equipment.[26] NIPA capital stock data by asset category for detailed industries are based upon many imputations and are likely to be measured with substantial error [Berndt and Morrison 1995]. Industry

25. The across-industry correlation (weighted by each industry's wage bill) of OCAM per FTE in 1980 and the proportion of workers using computers in 1984 is 0.74; the analogous correlation for OCAM per worker in 1990 and CPS computer utilization in 1989 is 0.77. The 1980–1990 change in OCAM per FTE has a (weighted) correlation of 0.47 with the change in computer usage from 1984 to 1993; and the log of average OCAM investment per FTE over the 1980s has a (weighted) correlation of 0.65 with the change in computer usage from 1984 to 1993.

26. Allen [1997] focuses on a narrower measure of high-tech capital (OCAM plus scientific and engineering instruments) and examines the relations of several industry-level technology indicators to changes in wages, returns to schooling, and educational employment shares from 1979 to 1989.

investment in many specific asset categories (such as OCAM) is not directly measured (at least at high frequency) by the Bureau of Economic Analysis, but is allocated across industries using capital flow tables and other "indicators" assumed to be correlated with industry commodity use (such as employment), and then further adjusted to match control totals from other reference sources [Gorman et al. 1985]. Despite these measurement problems, the NIPA data are the best available source of information on "high-tech" capital and overall capital intensity outside of the manufacturing sector.

Because the NIPA data only include private sector capital, we focus our empirical analysis of educational upgrading on 41 nonagricultural industries excluding service-sector aggregates with substantial government employment (e.g., health services and educational services).[27] Trends in the levels and log growth rates of capital intensity, OCAM as a share of the capital stock, OCAM per worker, and OCAM investment per worker for these industries are illustrated in Appendix 2. The rate of growth of the aggregate capital/labor ratio declined from the 1960s to the 1970s and then declined further in the 1980s, but this phenomenon is much more pronounced in nonmanufacturing industries.[28] While OCAM per worker is relatively stable from 1960 to 1970, it increases dramatically in the 1970s and 1980s.

Table VII presents a set of pooled cross-industry regressions covering 1960–1970, 1970–1980, and 1980–1990 of changes in the college graduate share of the wage bill on indicators of the rate of computer (OCAM) investment per worker and changes in overall capital intensity. Column (1) includes only time dummies for the 1970–1980 and 1980–1990 periods and illustrates an increase in the within-industry growth of the college wage-bill share in the 1970s and 1980s. Column (2) shows a positive contemporaneous relationship between decadal average computer investment per FTE and the change in the college payroll share. An examination of the coefficients on the time dummies in columns (1) and (2) indicates that the increased rate of computer investment per

27. We also exclude the "Nonmetallic minerals, except fuels" sector from the reported regressions since its low level of computer capital makes it an extreme outlier. The findings in Table VII are quite similar when this sector as well as the agricultural and other service industries are kept in the sample.

28. Significant problems in measuring changes in the quality of new capital goods have led some to question the accuracy of the NIPA price deflators for new investment (e.g., Gordon [1990]). Krusell et al. [1997] find using a quality-adjusted price index for equipment that the growth rate of the overall stock of new equipment did not decrease from the 1960s to the 1970s to the 1980s.

TABLE VII
COMPUTERS, CAPITAL INTENSITY, R&D, AND SKILL UPGRADING, 1960–1990 IN NONAGRICULTURAL, PREDOMINANTLY PRIVATE-SECTOR INDUSTRIES, DEPENDENT VARIABLE IS 100× (ANNUAL CHANGE IN THE COLLEGE GRADUATE WAGE-BILL SHARE)

							Non-manufacturing	Manufacturing	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Log $(CI/L)_{-1}$			.161		.138	.133	.177	.149	.076
			(.018)		(.024)	(.021)	(.028)	(.025)	(.044)
Log (CI/L)		.149		.130					
		(.020)		(.027)					
R&D$_{-1}$									7.885
									(2.249)
Δ Log (K/L)				.020	.024		.001	.136	.109
				(.015)	(.014)		(.010)	(.019)	(.016)
Δ Log (K/Y)						.014			
						(.011)			
Δ Log Y						.036			
						(.018)			
1970–1980	.297	.176	.318	.214	.341	.366	.417	.194	.119
dummy	(.041)	(.054)	(.042)	(.058)	(.043)	(.047)	(.048)	(.080)	(.080)
1980–1990	.482	.047	.320	.135	.381	.416	.307	.440	.417
dummy	(.072)	(.063)	(.070)	(.107)	(.085)	(.103)	(.102)	(.102)	(.093)
Intercept	.258	.926	.712	.771	.564	.470	.729	.244	.013
	(.037)	(.099)	(.065)	(.159)	(.107)	(.127)	(.118)	(.125)	(.148)
R^2	.309	.535	.525	.548	.546	.548	.667	.685	.809
Standard error	.301	.248	.250	.245	.246	.246	.212	.218	.174
n	123	123	123	123	123	123	63	60	42

The numbers in parentheses are Huber-White robust standard errors that allow for grouped errors by industry. Each column represents a pooled regression of decadal changes in the college graduate wage-bill share for 1960–1970, 1970–1980, and 1980–1990. Columns (1)–(6) include 41 NIPA nonagricultural, predominantly private-sector industries. Column (8) includes twenty manufacturing industries. Column (7) includes 21 nonmanufacturing industries. Column (9) includes fourteen manufacturing industries. Changes in the college graduate wage-bill share were calculated from the Census PUMS for 1960–1970 and 1970–1980 and from the CPS Merged Outgoing Rotation Group files for 1980–1990. *CI/L* and *K/L* were calculated from NIPA data. *Y* was calculated from the BLS Domestic Industry Output data. R&D was calculated from NSF data. All regressions are weighted by the product over the sum of the industry share of the total wage bill in each of the two years used in constructing the dependent variable. See the Data Appendix for details.

$(CI/L)_{-1}$ = log of five-year sum of real investment in office, computing, and accounting machinery per FTE in five years preceding start of decade.

(CI/L) = log of average annual real investment in office, computing, and accounting machinery per average FTE over decade.

R&D = Industry R&D funds as a percentage of net sales.

K/L = real net capital stock per FTE.

Y = real output.

Δ indicates 100 times the annual change in the variable.

worker can "account for" almost 40 percent of the increase in the rate of skill upgrading from the 1960s to the 1970s and overpredicts the further increase in the 1980s.[29] But the use of a contemporaneous measure of skill upgrading and computer investment raises concerns about possible reverse causation with other factors driving skill upgrading and then leading industries to equip their college workers with office machinery. Thus, we also explore whether previous computer investments produce subsequent skill upgrading as suggested by the firm-level results of Bresnahan, Brynjolfsson, and Hitt [1998]. Specifically, we also include a lagged measure of computer investment per worker. Column (3) indicates a positive and highly significant association of the log of an industry's OCAM investment per FTE in the five years prior to the start of each decade and that industry's growth of the college wage-bill share over the next ten years.[30]

The estimates in columns (4), (5), and (6) of Table VII indicate that the impact of computer investment on skill upgrading remains strong (using both contemporaneous and lagged computer investment measures) even when controls for changes in overall capital intensity and the growth in industry shipments are added to the specification.[31] Columns (5), (7), and (8) present identical parsimonious specifications for all private industries, nonmanufacturing, and manufacturing. The impact on the growth of the college wage-bill share of computer investment per FTE is similar in the manufacturing and nonmanufacturing sectors, but changes in overall capital intensity are much more important in the skill-upgrading process in the manufacturing sector.

We have performed multiple robustness checks of these findings. The results are almost identical when the total capital stock is replaced with the total stock of equipment, or if one uses measures of lags and changes in the OCAM capital stock per FTE rather than using measures of OCAM investment per FTE. The

29. Possible systematic inaccuracies in the price deflators for computers and other capital investments could bias estimates of the time effects and suggest that caution is required in comparing the coefficients on the time dummies across the specifications in Table VII.

30. In related contemporaneous work, Wolff [1996] finds that the log of OCAM expenditures per employee in the preceding seven years is positively associated with decadal changes in the fraction of "knowledge" workers in an industry in the 1970s and 1980s.

31. Column (6) adds the lagged computer investment variable as a proxy for skill-biased technological change to the basic specification for the share in total variable costs (total labor costs) of a variable input (college labor) when the cost function takes on a translog form, capital is treated as a quasi-fixed input, and the production function is allowed to be nonhomothetic (e.g., Berman, Bound, and Griliches [1994] and Goldin and Katz [1998]).

impacts of OCAM investments on skill upgrading are much stronger than those of other components of high-tech capital. If one allows the effect of the lagged log of computer investment per FTE to vary over time, the coefficient on computer investment is somewhat larger in the 1980s than in earlier decades. The findings are qualitatively quite similar when we use the college graduate share of employment as the dependent variable.[32]

We also examined the effect of another technology indicator—research and development (R&D) expenditures as a percentage of sales, which has been tabulated by the National Science Foundation [NSF]. As described in the Data Appendix, to use the R&D data, it is necessary to aggregate the NIPA industries to correspond to the NSF industry classifications, leaving fourteen manufacturing industries excluding Miscellaneous Manufacturing (an unstable composite). The weighted mean of R&D doubles between 1960 and 1990, increasing from 1.72 percent of sales in 1960 to 2.12 percent in 1970, 2.71 percent in 1980, and 3.54 percent in 1990.

Column (9) of Table VII reports estimates of a model that includes lagged R&D as a share of net sales for the fourteen manufacturing sector aggregates.[33] R&D intensity has a substantial positive impact on subsequent skill upgrading.[34] The inclusion of R&D reduces the computer investment coefficient, but lagged computer investment per FTE continues to positively predict skill upgrading.

VII. Skill Upgrading in Detailed Manufacturing Industries

Increased import competition and foreign outsourcing have been offered as alternative explanations to skill-biased technological change for the rapid rate of skill upgrading found in the U. S. manufacturing sector in the 1980s (e.g., Feenstra and Hanson [1996]). Data for more disaggregated industries on the skill composition of the workforce and indicators of technological

32. Mishel, Bernstein, and Schmitt [1997b] also find a strong positive effect of contemporaneous changes in computer capital per FTE on the college share of employment in regressions covering 1963 to 1994. They conclude that the impact of technology (measured by capital equipment intensity, computers, and scientists and engineers as a share of employment) on the within-industry growth of the college employment share accelerated from the 1960s to the 1970s but shows no further acceleration into the 1980s and 1990s.

33. A more complete set of specifications including R&D and computer variables is reported in Autor, Katz, and Krueger [1997].

34. Machin and Van Reenen [1998] also find substantial positive effects of R&D expenditures on the growth of "high skill" employment and wage-bill shares using higher frequency industry-level panel data for the United States, United Kingdom, Denmark, and Sweden.

change, international competition, and outsourcing are available in the manufacturing sector than in the nonmanufacturing sector. Consequently, we use data on 450 four-digit industries from the NBER Productivity Database (described in Bartelsman and Gray [1996]) for the 1959 to 1989 period to reexamine these alternative hypotheses. Information on the educational attainment of the workforce is not available at the four-digit industry level, so we follow Berman, Bound, and Griliches [1994] in using the change in the nonproduction worker share of the wage bill as our measure of skill upgrading. We link data on the change in nonproduction worker wage-bill share, changes in capital intensity, real shipments growth, and total factor productivity growth from the NBER Productivity sample with information on computer investments as a share of total investments from the Census of Manufactures, import and export penetration measures from Feenstra [1996, 1997], and the (broad) foreign outsourcing measure used by Feenstra and Hanson [1996].

The first five columns of Table VIII present a set of pooled cross-industry regressions covering 1959–1969, 1969–1979, and 1979–1989 attempting to explain changes in the nonproduction worker wage-bill share within four-digit manufacturing industries.[35] Column (1) documents the sharp increase in the rate of within-industry growth of nonproduction worker payroll share in the 1980s. The annual percentage point change in the nonproduction worker share of the total manufacturing wage bill increased from .110 for 1959–1969 to .126 for 1969–1979, and then shot up to .375 for 1979–1989. Column (2) includes the computer investment variable and indicates that the growth of the mean computer investment share from .026 in the 1970s to .057 in the 1980s can "account" for a rise of .09 percentage points annually (or 36 percent of the total increase) in the rate of within-industry skill upgrading from the 1970s to the 1980s in manufacturing.[36] Columns (3) and (4) indicate that the impact of computer investments is little changed when measures of overall capital intensity and output growth are included or when the specification is expanded to include another proxy for technological change (TFP

35. These particular years were chosen because they occur at reasonably similar points in the business cycle.

36. Berman, Bound, and Griliches [1994] similarly find in cross-industry regressions that the growth of the nonproduction worker wage-bill share from 1979 to 1987 is strongly positively related to computer investments as a share of total investment and to R&D over sales. But they do not examine whether the growth of computer investments can account for the increase in within-sector skill upgrading from the 1970s to the 1980s.

TABLE VIII
CHANGE IN THE NONPRODUCTION WORKER SHARE OF THE WAGE BILL IN 450 FOUR-DIGIT MANUFACTURING INDUSTRIES, 1959–1989, DEPENDENT VARIABLE IS 100× (ANNUAL CHANGE IN THE NONPRODUCTION WAGE-BILL SHARE)

	Pooled specifications					1959–1969	1969–1979	1979–1989
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Δ Log (*K/Y*)			.027	.029	.025	.011	.039	.049
			(.006)	(.009)	(.006)	(.010)	(.013)	(.010)
Δ Log *Y*			.019	.017	.018	.024	.032	.017
			(.006)	(.006)	(.006)	(.011)	(.014)	(.008)
CI/I		2.862	2.658	2.477	2.497	2.200	3.241	2.192
		(.620)	(.679)	(.693)	(.685)	(.679)	(1.175)	(.865)
Δ Log *TFP*				.010				
				(.015)				
Δ*Sm*				.019				
				(.055)				
Δ*Sx*				.052	.058	.126	.033	.066
				(.027)	(.028)	(.079)	(.040)	(.033)
Δ*So*				.052	.059	.053	.048	.116
				(.038)	(.049)	(.075)	(.052)	(.143)
1969–1979	.017	.016	.038	.011	.012			
dummy	(.046)	(.045)	(.040)	(.039)	(.039)			
1979–1989	.265	.175	.224	.211	.215			
dummy	(.037)	(.042)	(.045)	(.036)	(.041)			
Constant	.110	.037	−.051	−.062	−.057	−.076	−.096	.144
	(.031)	(.030)	(.031)	(.037)	(.031)	(.058)	(.050)	(.044)
R^2	.082	.180	.205	.220	.218	.144	.159	.215
n	1350	1350	1350	1350	1350	450	450	450
Standard error	.407	.385	.379	.376	.376	.330	.387	.394
Wtd. mean of dep var						.110	.126	.375

Standard errors are in parentheses. Huber-White robust standard errors are reported in all columns; the standard errors in columns (1)–(5) allow for grouped errors by four-digit industry. All regressions are weighted by the average industry share of the total manufacturing wage bill in the two years used in constructing the dependent variable. Δ indicates 100 times the annual change in the variable. *Sources*: Bartelsman and Gray [1996]; Berman, Bound, and Griliches [1994]; Feenstra [1996, 1997]; and Feenstra and Hanson [1996].

K/Y = Real capital stock to shipment ratio.
Y = Real value of shipments.
TFP = 5-factor total factor productivity.
Sm = Imports/(imports + shipments).
Sx = Exports/shipments.
CI/I = Ratio of computer investment to total investment.
So = Outsourcing = (imported inputs)/(total nonenergy material purchases).

CI/I: For 1959–1969 and 1969–1979 changes, *CI/I* is defined as the 1977 computer investment share; for 1979–1989 changes, *CI/I* is the average of the computer investment share in 1982 and 1987.

Δ*So*: For 1959–1969 changes, Δ*So* is 100 times the minimum of one-tenth of the level of outsourcing in 1972 and the annual change in outsourcing from 1972–1979; for 1969–1979 it is 100 times the annual change in outsourcing from 1972–1979; and for 1979–1989 it is the 100 times the annual change in outsourcing from 1979–1990.

The weighted mean of *CI/I* is .026 in 1959–1969, .026 in 1969–1979, and .057 in 1979–1989.

growth) and measures of the growth of imports, exports, and outsourcing. The overall growth of the log capital output ratio and growth in the exports-to-shipments ratios are both positively and significantly related to skill upgrading in the pooled model displayed in column (5). Outsourcing has a positive but not highly significant relationship to skill upgrading in specifications including the computer investment variable.[37] The effect of computer investment on skill upgrading is quite similar when the specifications reported in columns (2) to (5) are expanded to include four-digit industry fixed effects.

Columns (6), (7), and (8) of Table VIII relax the constraint that the coefficients are the same across decades, and present separate regressions by decade analogous to the pooled specification in column (5). Computer investment remains a powerful explanatory variable in all three decades. The coefficient on overall capital intensity increases over time, suggesting a possible secular rise in the magnitude of capital-skill complementarity in U. S. manufacturing from the 1960s to the 1980s.

In summary, the estimates in Table VIII indicate that the growth in the computer investment ratio can "explain" approximately one-third of the increase in within-industry skill upgrading in U. S. manufacturing from the 1970s to the 1980s, under the rather strong assumption that the estimated effect of computer investment represents a causal impact of computer investment on skill demands. Changes in import penetration and outsourcing are not strong predictors of skill upgrading conditional on the computer investment ratio, but industries with expanding export shares appear to have faster growth in nonproduction worker payroll share.[38]

VIII. Conclusions

Studies of the role of skill-biased technological change in the recent widening of the U. S. wage structure should take a longer-term perspective than just the last two decades. An analysis of the time pattern of aggregate changes in the relative

37. Outsourcing has a strong positive and significant effect in pooled specifications only including the outsourcing measure and time dummies. We find a similar pattern of results when we use the narrow outsourcing measure (imported intermediate inputs in the same two-digit industry as buyer as a share of total nonenergy materials purchases) of Feenstra and Hanson [1998].

38. Bernard and Jensen [1997] similarly find for detailed manufacturing industries from 1980 to 1987 that export growth is strongly positively correlated with between-plant shifts of employment to plants employing more-skilled workers and with within-plant skill upgrading.

supply, relative wage, and relative wage-bill share of college graduates over the 1940 to 1996 period suggests strong secular relative demand growth favoring highly educated workers that has persisted throughout the past five decades. While the rate of relative demand growth for college workers appears to have been particularly rapid in the 1980s, our data do not unambiguously indicate whether or not the trend rate of overall growth in the relative demand for skilled workers has increased in recent decades. Indeed, our results suggest a slowdown in overall relative demand growth in the first half of the 1990s.

But the pace of within-industry skill upgrading increased from the 1960s to the 1970s throughout the economy, accelerated further in manufacturing from the 1970s to the 1980s, and remained high from 1990 to 1996. Indicators of employee computer usage, computer capital per worker, and the rate of computer investment are higher in industries with more rapid rates of skill upgrading in each of the last several decades, and in industries with larger accelerations in skill upgrading in the 1970s and 1980s versus the 1960s. Thus, skill-biased technological and organizational changes that accompanied the computer revolution appear to have contributed to faster growth in relative skill demand within detailed industries starting in the 1970s. Although the strong observed conditional correlations of computer measures and the growth in the relative utilization of highly educated workers may not just reflect causal relationships, it seems clear that whatever is driving the rapid rate of within-industry skill upgrading over the past few decades is concentrated in the most computer-intensive sectors of the U. S. economy. These patterns leave much room for fluctuations in the rate of growth of the supply of college equivalents, globalization forces, and changes in labor market institutions to have contributed to recent movements in U. S. educational wage differentials.

Data Appendix

A.1. Computer Use in the Current Population Survey

Industry computer use frequencies were calculated from the October 1984, 1989, and 1993 School Enrollment Supplements to the Current Population Survey (CPS) as the weighted fraction of currently employed workers ages 18–65 who answered yes to the question, "Do you use a computer directly at work?" within consistent Census Industry Code (CIC) industries (see below). A computer is defined as a desktop terminal or PC with keyboard and monitor and does not include an electronic cash register or a hand-held data device. 62,005, 63,085, and 60,156 observations were used to calculate these frequencies in 1984, 1989, and 1993, respectively.

A.2. Samples Used from the CPS

We used the Merged Outgoing Rotation Group (MORG) files of the Current Population Survey for the years 1980, 1990, and 1996, and the February 1990 CPS, to calculate educational employment shares, educational full-time employment equivalent (FTE) shares, and educational wage-bill shares. Samples were limited to those currently employed in the sample reference week including the self-employed and excluding those working without pay. Top-coded earnings observations were multiplied by 1.5. Log wage regressions used to calculate the college-plus/high school premiums reported in Tables I and II were limited to wage and salary workers. The bottom 1 percent of hourly earners was dropped in each earnings regression. All CPS calculations were performed using the sampling weights for the outgoing rotation groups.

Educational employment shares by industry were calculated as the fraction of employed in each of four educational categories (less than high school, high school, some college, and college plus). The share of FTEs supplied by each education group in an industry is the sum of usual weekly hours reported by education category divided by total hours reported. Because the self-employed do not report hours or earnings, we assigned them the average labor hours and earnings in their industry-education-year cell. In the rare cases where industry hours supplied by education category were unavailable (where all sampled workers in the cell were self-employed), we imputed weekly hours as 40 per worker. Wage-bill shares are the sum of weekly earnings in an industry-education cell divided by total weekly earnings in the industry. Where earnings were not observed in an industry-education-year cell, we assigned the mean education-year wage.

To overcome potential inconsistencies in the reporting of usual hours in the revised CPS, we assigned workers with fewer than 8 weekly hours the mean hourly wage for other part-time workers (those with 8–35 weekly hours) in their industry-education-year-cell when calculating wage-bill shares in 1990 and 1996. When estimating log earnings regressions for 1990 and 1996, we limited the sample to full-time workers.

In addition to the CPS samples noted above, Table V uses the CPS MORG files from 1979 and 1993. The sample criteria are identical to those above except that self-employed workers were excluded. To calculate lagged industry educational levels, we used the 1974 May CPS file.

A.3. Samples Used from the Census

To calculate educational shares of employment, FTE, and the wage bill, we used currently employed workers ages 18–65 from the Census PUMS for 1940, 1950, 1960, 1970, 1980, and 1990. Self-employed workers were retained, while those working without pay were excluded. We calculated education shares, FTE shares, and wage-bill shares as we did in the CPS, with the exception that FTEs were not imputed to any observations since the self-employed report hours in the Census. We calculated hourly wages as the ratio of wage and salary earnings in the previous year to the product of weeks worked in the previous year and hours worked in the survey reference week. Although usual hours in the previous year (as opposed to the reference week) are available in some Census samples, we used hours worked in the reference week for all wage calculations for consistency. In 1940 the Census questionnaire asked respondents to report full-time equivalent weeks worked instead of calendar weeks worked, and hence we calculated hourly earnings in 1940 as the ratio of annual income to reported weeks. In all years, wages were imputed to the currently self-employed and those with missing income as described above. Top coded income observations were multiplied by 1.5 in each year. Because, in 1990, Census income top-codes varied by state (but were always at or above 140,000), we assigned top-coded observations the value of 210,000. Because both weeks-worked and hours-worked variables are intervalled in 1960 and 1970, we used the midpoint of each interval in lieu of the actual value. Sampling weights were used for all Census calculations in 1940 and 1990 samples.

A.4. Changes to the Coding of the Educational Variable after 1990 in the Census and CPS

Prior to the 1990 Census and the 1992 CPS, the Census Bureau coded respondents' educational level accorded to their highest grade completed. Starting in the 1990 Census and 1992 CPS, the questionnaire was changed to record the highest degree held or, when no degree is held, whether the highest grade attained falls within certain multiyear categories. This change creates substantial incompatibilities in comparing educational levels among CPS or Census samples across the coding regimes. Following the recommendations of Jaeger [1997], we use the following educational groupings. In data coded with the old (years completed) education question (Census PUMS 1940, 1950, 1960, 1970, and 1980, and CPS MORG files 1980 and 1990), we defined high school dropouts as those with fewer than twelve years of completed schooling; high school graduates as those having twelve years of completed schooling; some college attendees as those with any schooling beyond twelve years (completed or not) and less than sixteen completed years; and college plus graduates as those with sixteen or more years of completed schooling. In data coded with the new question (1990 Census PUMS, February 1990 CPS, 1996 CPS MORG file), we define high school dropouts as those with fewer than twelve years of completed schooling; high school graduates as those with either twelve completed years of schooling or a high school diploma or G.E.D.; some college as those attending some college or holding an Associate's Degree (either occupational/vocational or academic); and college plus as those with a B.A. or higher. The 1940 Census does not report whether years of schooling have been completed, and hence, for this sample, we included all those with twelve years of reported education as high school graduates. In log earnings regressions where we distinguish college graduates from those with postcollege education, we define postcollege as seventeen plus completed years of schooling (years-based question) or any degree held beyond the B.A. (degree-based question). For CPS samples found in Tables IV and V, we used the conventional definitions of each education category.

For 1990–1996 changes in the college wage premium, we used the February 1990 CPS in conjunction with the 1996 MORG file since differences between the earnings concepts in the Census and CPS (annual versus weekly) makes direct Census-CPS comparisons of wages unreliable. Because the February 1990 CPS contains both the old and new education questions, the February 1990 to 1996 MORG comparison is not hampered by the change to the education question. Two other difficulties result from using the February 1990 CPS, however. First, because the February 1990 survey contains both education questions, it is possible that responses to the degrees-completed question were skewed by the prior asking of the years-completed question. Second, since the February 1990 CPS contains only a single month's data, the sample is only one-third as large as the annual MORG file for industry employment and only one-twelfth as large for hours and earnings.

In estimating the log earnings regressions for post-1992 CPS samples (degree-based education question), we use figures from Park [1994] to assign years of completed education to each worker based upon race, gender, and highest degree held. Years of potential experience were calculated as age minus assigned years of education minus six.

A.5. Consistent Industry and Occupation Codes

Although a majority of the Census Industries Codes (CICs) have remained intact since 1960 (aside from renumbering), many new industry categories have emerged from larger aggregates, while some detailed categories were collapsed or eliminated. During a major revision to the CIC in 1980, many industries were intertwined such that one or more old codes concorded with more than one new code. Our strategy for creating a consistent set of codes spanning the 1960, 1970, 1980 and 1990 CIC standard was to preserve industries that were present in all years, while recombining industries that were disaggregated in later years or that became intertwined during later revisions. Although in most cases it was unambiguous whether industries should be retained intact or merged, in the cases where there was minimal (but nonzero) overlap among industries, we compromised in favor of preserving detail rather than enforcing perfect consistency. The resulting set of consistent industry codes contains 142 distinct industries for the 1960–1990 period, as compared with 149 industries in 1960, 213 in 1970, 231 in 1980, and 236 in 1990. We also created consistent industry codes spanning the 1970 to 1990 period which are used in the models in Table V. Because the 1960 codes impose the greatest cost in lost detail, the 1970–1990 codes (which exclude 1960 CICs) contain 52 additional distinct industries (a total of 194). Many of the reported estimates were performed at several levels of CIC detail to test their sensitivity to aggregation. In general, aggregation has little effect on the estimated coefficients. Crosswalks between the 142 consistent CIC and the 1960, 1970, 1980, and 1990 CIC standard are available from the authors.

A.6. Data from the National Income and Product Accounts and on Industry Output

We used data on capital stock (equipment, structures, and total) and investment in Office Computing and Machinery (OCAM) from the National Income and Product Accounts (NIPA) to measure capital intensity and high-tech capital holdings at the industry level between 1950–1990. As the denominator for our capital/FTE and equipment/FTE variables, we used NIPA data to calculate FTEs by industry in 1960, 1970, 1980, and 1990. To reduce measurement error, all variables in the NIPA (aside from FTEs and cumulative investment measures) were constructed as five-year centered averages of the respective data category. All NIPA stock and investment variables are measured in real 1987 dollars. Deflation of NIPA measures is performed by the Bureau of Economic Analysis using primarily Producer Price Indexes (PPIs). PPIs for computer investment are based on quality adjustment, price linking, and hedonic regression methods. See U. S. Department of Commerce [1993] for details.

To match CPS and Census data to the NIPA, we created a crosswalk between the NIPA categories (based on the SIC) and our 142 consistent CIC categories. The resulting aggregation of NIPA and CIC data contains 47 consistent industries covering all industrial sectors excluding Government and Private Households, spanning the 1960–1990 CIC and the 1972 and 1987 Standard Industrial Classification (SIC). This crosswalk is available upon request.

To construct the real industry output variable, we used the Bureau of Labor Statistics Industry Employment and Output Series which contains estimates of domestic industry output for 183 sectors in constant dollars from 1958 through the present. We matched the 183 BLS sectors to the 47 consistent NIPA sectors and, as above, used five-year centered averages to calculate the value of output by sector.

A.7. Four-Digit SIC Manufacturing Data

We used the NBER Productivity Database created by Eric Bartelsman and Wayne Gray for analysis of skill upgrading in four-digit SIC manufacturing industries. Documentation on this database is available from the NBER web site (http://www.nber.org). Gordon Hanson and Robert Feenstra graciously provided outsourcing data used in Feenstra and Hanson [1996, 1998]. Annual Survey of Manufacturers (ASM) data on computer investment at the four-digit SIC level for 1977, 1982, and 1987 was provided by Eli Berman (see Berman, Bound, and Griliches [1994] for details).

A.8. Research and Development Expenditures Data

As a measure of industry R&D intensity, we used data from the National Science Foundation's [NSF] Research and Development in Industry series on company and other (except Federal) R&D funds as a percentage of net sales in R&D-performing manufacturing companies. To analyze these data in conjunction with the NIPA, we created an aggregate NIPA-NSF crosswalk that divides the manufacturing sector into fifteen consistent industries for the 1960–1995 period. This crosswalk is available upon request from the authors. Due to missing observations in the NSF data, several imputations and interpolations were required. We thank Nachum Sicherman for generous assistance with the NSF data.

APPENDIX 1: EMPLOYMENT AND WAGE-BILL SHARES BY EDUCATIONAL CATEGORY, 1940–1996

A. Employment shares (in percent): 1940–1996

	High school dropouts	High school graduates	Some college	College graduates	College equivalents
1940 Census	68.4	19.1	6.4	6.1	9.3
1950 Census	58.5	24.3	9.5	7.7	12.4
1960 Census	50.0	27.4	12.5	10.1	16.4
1970 Census	36.1	34.1	16.4	13.4	21.5
1980 Census	21.4	35.8	23.6	19.2	31.0
1980 CPS	19.3	38.0	22.8	19.9	31.3
1990 CPS	13.1	36.3	26.0	24.6	37.6
1990 Census	12.0	33.3	30.8	24.0	39.3
Feb. 90 CPS	12.0	37.0	26.1	24.9	38.0
1996 CPS	9.8	33.7	29.8	26.7	41.6

B. Wage-bill shares (in percent): 1940–1996

	High school dropouts	High school graduates	Some college	College graduates	College equivalents
1940 Census	58.3	20.6	8.9	12.3	16.7
1950 Census	52.1	25.0	11.0	11.9	17.4
1960 Census	42.4	27.1	14.1	16.4	23.4
1970 Census	29.7	32.3	16.5	21.5	29.7
1980 Census	17.0	32.5	22.4	28.1	39.3
1980 CPS	15.4	34.2	21.8	28.5	39.5
1990 CPS	8.6	29.9	24.2	37.3	49.4
1990 Census	8.0	26.8	28.5	36.7	51.0
Feb. 90 CPS	7.8	29.9	25.0	37.2	49.7
1996 CPS	5.8	27.0	26.6	40.6	53.9

Employment and wage-bill shares are calculated from the samples described in the notes to Table I. College equivalents are defined as those with a college education plus half of those with some college. See the Data Appendix for details.

APPENDIX 2: CAPITAL AND COMPUTER MEASURES 1960–1990: LEVELS AND 100× (ANNUAL LOG CHANGES) IN NONAGRICULTURAL, PREDOMINANTLY PRIVATE SECTOR INDUSTRIES

	All sectors				Manufacturing				Nonmanufacturing			
Panel A: Levels by decade	1960	1970	1980	1990	1960	1970	1980	1990	1960	1970	1980	1990
Capital stock/FTE	42.67	54.94	72.01	86.33	25.98	33.60	47.22	59.29	56.10	70.09	87.42	99.44
OCAM/capital stock	0.004	0.003	0.010	0.046	0.003	0.003	0.009	0.040	0.004	0.003	0.010	0.049
OCAM/FTE	0.072	0.064	0.332	2.545	0.073	0.063	0.317	1.986	0.071	0.064	0.341	2.817
Decadal OCAM investment/FTE	0.016	0.015	0.045	0.439	0.017	0.014	0.041	0.341	0.015	0.016	0.048	0.485
Panel B: 100× (annual log changes)		60–70	70–80	80–90		60–70	70–80	80–90		60–70	70–80	80–90
Capital stock/FTE		3.41	2.31	1.86		3.45	3.34	2.78		3.37	1.63	1.36
OCAM/capital stock		−4.81	11.35	16.96		−3.68	11.88	14.80		−5.65	10.99	18.14
OCAM/FTE		−1.40	13.66	18.82		−0.23	15.22	17.58		−2.28	12.62	19.50
Decadal OCAM investment/FTE		0.41	7.76	21.11		0.46	9.92	20.45		0.38	6.33	21.46

Figures are tabulated for the 41 National Income and Product Accounts (NIPA) nonagricultural, predominantly private-sector industries (20 in manufacturing, 21 in nonmanufacturing) found in Table VII. Capital measures and FTEs are drawn from the National Income and Product Accounts (NIPA). Each measure is a five-year centered average of the respective variable (except for FTEs and OCAM investment). FTEs are measured in thousands. Capital and investment measures are in millions of constant 1987 dollars. OCAM is Office Computing and Accounting Machinery. All stock variables are net stock measures. Decadal investment is 0.1 times cumulative real investment over previous ten years. Panel B is calculated as the 100 times the annual change in the log of each of the variables in panel A during the indicated ten-year period. Figures in panel A are weighted by industry share in the total wage bill in each year. Figures in panel B are weighted by the product over the sum of the industry share of the total wage bill in each of the two years used in calculating the measure. See the Data Appendix for details.

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