Technology, Skill, and the Wage Structure: Insights from the Past

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Recent technological advances and a widening of the wage structure have led many to conclude that technology and human capital are relative complements. The possibility that such a relationship exists today has prompted a widely held conjecture that technology and skill have always been relative complements. According to this view, technological advance always serves to widen the wage structure, and only large injections of education slow its relentless course. A related literature demonstrates that capital and skill are relative complements today and in the recent past (Zvi Griliches, 1969). Thus capital deepening appears also to have increased the relative demand for the educated, serving further to stretch the wage structure. Physical capital and technology are now regarded as the relative complements of human capital, but have they been so for the past two centuries?

Some answers have already been provided. A literature has emerged on the bias to technological change across history that challenges the view that physical capital and human capital have always been relative complements. Many of the major technological advances of the 19th century substituted physical capital, raw materials, and unskilled labor for highly skilled artisans (John A. James and Jonathan S. Skinner, 1985). But if physical capital and human skill were not always relative complements, when did they become so, and when did new technology become skilled labor's complement?

We argue that capital–skill complementarity was manifested in the aggregate economy as particular technologies spread, specifically batch and continuous-process methods of production. Across the past two centuries, manufacturing shifted first from artisanal to mechanized and nonmechanized factory production, then from simple factories to assembly lines, and finally from assembly lines to continuous and batch processes. Although few products were manufactured by more than two of the technologies mentioned, manufacturing, as a whole, progressed in the fashion described.

In considering our argument it is useful to envision manufacturing as having two distinct stages: (i) a machine-installation and machine-maintenance segment and (ii) a production or assembly portion. Capital and educated (skilled) labor, we will argue, are *always* complements in the machine-maintenance segment of manufacturing, regardless of the technology. Machinists, for example, are needed to install machinery and make it run. The workable capital created by skilled labor plus raw capital is then used by unskilled labor to create the final product in the production or assembly segment of manufacturing. How the adoption of a technology alters the relative demand for skilled workers will depend on whether the machine-maintenance demand for skilled labor is offset by the production-process demand for unskilled labor.

I. Capital–Skill Complementarity: The Historical Record, 1909–1940

For the past, as well as today, the data that might reveal capital–skill complementary are

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imperfect. The 1909 and 1919 U.S. Censuses of Manufactures contain data on the capital stock, but production workers were not disaggregated, except by sex and by child versus adult, and no information on skill or education was asked. White-collar workers, however, were categorized in some detail: generally, proprietors and firm members; salaried officers of corporations; superintendents, managers, engineers, and other technical experts; and clerks, stenographers, salesmen, and other salaried employees. Beginning in 1940 the U.S. Census of Population asked for highest grade of school completed, industry, and occupation. Using these sources, and the narrative historical record, we trace the origins of capital–skill and technology–skill complementarity.

We find, looking across narrowly defined industries in 1909 and 1919 (U.S. Department of Commerce, 1913, 1924), that high-education industries, categorized on the basis of 1940 data (Inter-university Consortium for Political and Social Research [ICPSR], 1984) were generally more capital-intensive in the 1909–1919 period. They also paid their production workers more in both 1909 and 1919, suggesting that their workers were more skilled from 1909 to 1940. Industries that were high-education in 1940 but not highly capital-intensive in 1909 and 1919 often produced the newer products of the day (e.g., electrical, home, and office machinery, aircraft) or were artisanal crafts (and printing and publishing).

Many of the industries we classify as capital-intensive and high-education have been categorized by others as employing continuous-process or batch technologies (Alfred D. Chandler, Jr., 1977). The evidence for the 1909–1919 period is consistent with the notion that the transition to these processes increased the relative demand for skilled workers, whereas the previous transition, from the artisanal shop to the factory, decreased it. Yet across all manufacturing, capital and skill appear to be complementary. We find for 1909–1919 that the change in the proportion of the wage bill going to white-collar workers is positively related to the change in capital-intensity of the industry. The coefficient measuring capital–skill complementarity for 1909–1919, moreover, is larger than it is for 1959–1969 and 1969–1979 and about equal to that for 1979–1989.

A. *Educated Labor in Blue-Collar Occupations*

Among all 18- to 34-year-old, male, blue-collar workers in the 1940 Public-Use Microdata Sample (ICPSR, 1984), 27.6 percent stated they had completed 12 years of schooling. As a fraction of the total blue-collar work force, these workers were found disproportionately in industries using continuous-process and batch technologies (petroleum refining, dairy products, paints and varnishes, miscellaneous chemicals, rayon, nonferrous metals) and in high-technology industries such as the products or services of electricity, the telephone, radio, and aircraft. The industries therefore divide into two categories. At the low end of the education distribution are the products of the first industrial revolution: cotton, woolen, and silk textiles, boots and shoes, lumber, stone, clay, and cement. At the other extreme are the newer goods and services of the second industrial revolution.

The categorization of the high-education industries is not generated solely by geographic differences in both education and industry, by age differences in employment and educational attainment, or by whether particular occupations dominate an industry. Nor is the distribution of educated workers by industry in 1940 solely a product of the Depression, as results from 1950 and 1960 show. Firms in 1940, moreover, paid their higher-educated, blue-collar workers more. We estimate that the rate of return to a year of education, in a standard earnings equation for white male blue-collar workers (18–34 years old), was 8.3 percent, whereas it was 8.9 percent for an equivalent group of ordinary white-collar workers.

To investigate capital–education complementarity in the 1909–1940 period, we merge the education data by industry from the 1940 census with that on industry attributes from the 1909 and 1919 Censuses of Manufactures.

The ratio of the capital stock to the number of wage earners in 1909 and 1919 is positively related to the education of workers in

TABLE 1—EDUCATION AND THE RATIO OF CAPITAL TO LABOR IN 1909 AND 1919

	Regression coefficients		
Independent variable	(i) 1909	(ii) 1919	(iii) 1909
$\ln(K/L)$	0.0620 (0.0176)	0.0328 (0.0236)	0.0565 (0.0165)
$d\ln(K)$			0.0587 (0.0197)
Percentage artisan	0.200 (0.0347)	0.204 (0.0441)	0.209 (0.0325)
Percentage female	0.135 (0.0549)	0.0144 (0.0672)	0.0925 (0.0532)
Percentage children	−1.60 (0.380)	−2.16 (0.901)	−1.56 (0.354)
Constant	0.197 (0.0238)	0.223 (0.0423)	0.162 (0.0250)
Mean of dependent variable:	0.251	0.267	0.251
Number of observations:	57	57	57
R^2:	0.546	0.379	0.613

Notes: Regressions are weighted by the number of wage-earners in each 1909 and 1919 industry. Standard errors are in parentheses. The dependent variable is the percentage of 18–34-year-old, male blue-collar workers, by industry in 1940, who graduated from high school. The 256 1909- and 1919-industries are aggregated up to the 57 1940 groupings. K = capital stock (1,000's of current U.S. dollars) in each 1909 and 1919 industry; L = number of wage-earners; $d\ln(K) = \ln(K)_{1919} - \ln(K)_{1909}$; percentage artisan = the fraction of wage earners in the 1940-industry category who were in an artisanal trade in 1909 and 1919 (percentage female and percentage children are similarly defined).

Sources: U.S. Department of Commerce (1913, 1924); 1940 Public-Use Microdata Sample, 1/100 (ICPSR, 1984).

1940 by industry (see Table 1). The effect, moreover, is economically significant. An increase in the capital-to-labor ratio by the equivalent of the difference between the lumber and timber industry and the oleomargarine industry in 1909 is associated with an increase of 7.7 percentage points in the high-school graduation rate, the overall mean of which in 1940 was 28 percent. Furthermore, a faster increase in capital from 1909 to 1919 is positively correlated with wage-earners' education in the industry.

More capital-intensive industries and those with greater growth in the capital stock employed a more highly educated labor force some 20 years later. We do not mean to imply that there is any direct relationship between individual workers in 1909 (or 1919) and 1940. But we are claiming that something about these industries increased the value of secondary-school education during the 1909–1940 period. Secondary schooling in the 1910's was just beginning to affect the education of the masses, but by the period from the mid-1920's to the mid-1930's about 30–50 percent of youths had high-school diplomas. Skilled workers in 1909 and 1919 may have been replaced in subsequent decades by young high-school graduates, as formal education was substituted for on-the-job training and apprenticeships. High-school graduates were highly valued because they could read manuals and decipher blueprints, had knowledge of chemistry and electricity, could do simple algebra, and might converse intelligibly with the professional staff.

In 1909 and 1919, firms in the high-education industries paid significantly more for their production workers. The average blue-collar wage in both 1909 and 1919 is strongly and positively related to the education level in the industry in 1940 and the implied return to a year of schooling is 10–12 percent:

$$(1)\quad \ln(\text{wage})_{i,1909} = \underset{(0.102)}{5.22} + \underset{(0.0111)}{0.124}\,(\text{education})_{j,1940} - \underset{(0.0681)}{0.494}\,(\%[\text{female} + \text{child}])_{i,1909}$$

(number of observations = 218, $R^2 = 0.692$, $\hat{\sigma} = 0.119$), where the wage is in current dollars for industry i in 1909, education is mean years of schooling in 1940 for 18–34-year-old blue-collar males by 1940-industry (j) groups, and the percentage of females and children among wage earners is for the 1909 industry. Numbers in parentheses are standard errors. The regression is estimated with Huber (White) standard errors, allowing for correlation in the errors within the 1940 groups and is weighted by the number of wage earners by industry. The estimation for 1919 yields similar results.

B. *Capital–Skill Complementarity and Nonproduction Workers*

The data for 1909 and 1919 allow another test of the capital–skill complementarity hypothesis, as well as a comparison with more recent estimates, by examining whether the nonproduction-worker share of total labor costs increased along with the ratio of capital to output. Continuous-process and batch methods required more managerial and professional workers relative to production workers (Chandler, 1977) and, we suspect, a greater fraction of blue-collar workers who were skilled. The share of nonproduction workers in manufacturing increased during the decade, from 13.9 percent in 1909 to 15.7 percent in 1919, although their relative wages decreased.

The estimating equation comes from a model in which capital is considered the quasi-fixed factor during each decade, and nonproduction (skilled or educated) and production (unskilled) labor are the variable factors (for details see Eli Berman, et al. [1994]). If the variable (total labor) cost function for industry j is translog and production exhibits constant returns to scale, then cost minimization produces the following equation for the nonproduction labor share of total labor costs (S) in time t:

$$(2) \qquad S_{tj} = \alpha_j + \phi_j t + \gamma_j \ln(w_n/w_p)_j + \rho_j \ln(K/Y)_j$$

where w_n (w_p) is the wage of nonproduction (production) workers, (K/Y) is the capital-to-output ratio, and ϕ_j measures the rate of skill-biased technological change in industry j. Differencing (2) to eliminate industry fixed-effects yields the following estimating equation for the change in the nonproduction share of the wage bill in industry j:

$$(3) \qquad dS_{jt} = \beta_0 + \beta_1 d\ln(w_n/w_p)_{jt} + \beta_2 d\ln(K/Y)_{jt} + \varepsilon_{jt}.$$

The coefficient β_1 is greater than or less than 0 depending on whether the elasticity of substitution between nonproduction and production labor is less than or greater than 1; $\beta_2 > 0$ implies capital–skill complementarity; and β_0 captures the cross-industry average of the skill bias to technical change, with ($\beta_0 + \varepsilon_{jt}$) being the industry-specific bias to technical change. The intuitive interpretation of $\beta_2 > 0$ is that industries with a greater increase in capital intensity are those with a larger increase in the nonproduction-worker share of total labor costs. We estimate a version of (3) in which the relative-wage term is dropped (subsumed in a time effect) and an ad hoc output term is included.

TABLE 2—CHANGE IN THE NONPRODUCTION-WORKER SHARE OF WAGE BILL: 1909–1919, 1959–1969, 1969–1979, AND 1979–1989

Independent variable	(i) 1909–1919	(ii) 1959–1969	(iii) 1969–1979	(iv) 1979–1989
$d\ln(K/Y)$	0.051	0.018	0.040	0.061
	(0.012)	(0.006)	(0.009)	(0.011)
$d\ln(Y)$	−0.008	0.026	0.021	0.036
	(0.004)	(0.006)	(0.008)	(0.007)
Constant	0.018	−0.003	0.005	0.030
	(0.003)	(0.004)	(0.003)	(0.002)
R^2:	0.109	0.040	0.040	0.071
$\hat{\sigma}$:	0.0369	0.0348	0.0412	0.0427
Number of observations:	256	450	450	450
Mean of dependent variable:	0.006	0.011	0.013	0.037

Notes: The dependent variable is the change in the nonproduction-worker share of the wage bill between the years given. An observation is an industry, generally at the (pseudo-) four-digit SIC level. Regressions and the mean of the dependent variable are weighted by the average wage-bill share between the years given. Standard errors are in parentheses. K = capital stock, and Y = shipments; $d\ln(Y)$ is deflated by the wholesale price index for 1909–1919 and by the producer price index for finished goods in the other three periods.

Sources: U.S. Department of Commerce (1913, 1924) and NBER Manufacturing Productivity Database, Annual Survey of Manufacturers, as described in Eric Bartelsman and Wayne Gray (1994). For price deflators for 1909 and 1919: U.S. Department of Commerce (1975 [series E-40]).

The data are matched by (pseudo-) four-digit SIC industry (there are 256) for 1909 and 1919, the last year until 1957 that the Census of Manufactures inquired about the capital stock. Nonproduction workers are listed in four groups: proprietors, officers, managers, and clerical staff (see also Section I). The results for 1909–1919, given in column (i) of Table 2 demonstrate that the coefficient on the change in the (ln) capital/output ratio (β_2) is positive and significant. It remains so regardless of other controls and is robust to the choice of output measure (shipments or value added) and the inclusion of the relative-wage term.

How large we think the effects are will depend on their magnitude for more recent years, a period for which many have concluded, on the basis of such regressions, that capital–skill complementarity exists. We present such a comparison in columns (ii)–(iv) for 1959–1969, 1969–1979, and 1979–1989. The striking finding is that the coefficient on the change in the (ln) capital/output ratio (β_2) is largest for 1909–1919 and 1979–1989, suggesting a strong movement during the 1910's toward capital–skill complementarity possibly similar to recent changes associated with the microcomputer revolution.

II. Historical Insights and Conclusion

We are often told that ours is a time of extraordinary technological change. Yet consider that of the two decades around 1915. Barely 10 percent of American households had electricity in 1905 but 50 percent did by 1925; whereas 10 percent of all manufacturing horsepower was in the form of electricity in 1905, 70 percent was electric in 1925. Aircraft, aluminum, the radio, and the electric refrigerator were virtually unknown in 1909, yet were vibrant industries by 1925. Only one radio broadcast station existed in 1921, yet there were 681 in 1927. The office may be undergoing a revolution today, but consider the range of machinery that diffused in the 1910's: calculators, dictating machines, copying equipment, the keypunch, and the typewriter. All the products just mentioned were the outputs of industries we identify as high-education in 1940 and that appear to have employed a relatively skilled blue-collar group in the 1910's.

The technologically forward industries of the day were also those that grew most rapidly. The shift was most pronounced in the 1910's. If a high-education industry is one in which more than one-third of its young male blue-collar workers had a high-school degree in 1940, the share of high-education manufacturing employment increased from 19.7 percent in 1909 to 24.7 percent in 1919. The share of manufacturing employment in the top five (two-digit) SIC industries by education (petroleum, chemicals, electrical machinery, printing and publishing, and scientific instruments) continued to expand from 1920 to 1940 (from 11.1 percent to 15.9 percent). Similar shifts today reinforce the impacts of capital–skill and technology–skill complementarity.

But what did these changes mean for the wage structure, the subject that prompted our study? On the shop floor and in the office and executive suite the relative demand for skilled and educated labor must have increased greatly during 1910–1940. The response was overwhelming: in thousands of school districts across America, high schools mushroomed, curricula were updated, and enrollments soared. The earnings differential between the high-school-educated blue- or white-collar employee and the less-educated worker was thereby kept in check (Goldin and Katz, 1995).

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