THE ORIGINS OF TECHNOLOGY-SKILL COMPLEMENTARITY*

CLAUDIA GOLDIN AND LAWRENCE F. KATZ

Current concern with the impact of new technologies on the wage structure motivates this study. We offer evidence that technology-skill and capital-skill (relative) complementarities existed in manufacturing early in this century and were related to the adoption of electric motors and particular production methods. Industries, from 1909 to 1929, with more capital per worker and a greater proportion of motive energy coming from purchased electricity employed relatively more educated blue-collar workers in 1940 and paid their production workers substantially more. We also find a strong positive association between changes in capital intensity and the nonproduction worker wage bill from 1909–1919 implying capital-skill complementarity as large as in recent years.

The recent coincidence of computerization and a widening wage structure has led many to conclude that new technologies and human capital are relative complements and that large injections of education may be necessary to reduce the impact of advancing technology on inequality.[1] In a related literature, physical capital and skill have been shown to be relative complements both today and in the recent past.[2] These findings, taken

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[1] For models and (indirect) evidence on the relationship between new technologies and the relative demand for skill, see, e.g., Bound and Johnson [1992], Greenwood [1997], Greenwood and Yorukoglu [1997], Katz and Murphy [1992], and Krusell et al. [1997]. Tinbergen [1975] has characterized the evolution of the wage structure as a "race between technological development and access to education." Direct intervention in wage setting by governments and labor unions can, of course, also alter the wage structure.

[2] The empirical research covering the post-World War II period, beginning with Griliches [1969] and summarized by Hamermesh [1993], supports the capital-skill and technology-skill complementarity hypotheses. Bartel and Lichtenberg [1987] find, from a panel of manufacturing industries from 1960 to 1980, that the implementation of new technologies, proxied by the age of the capital stock, increases the share of the highly educated in total labor cost. Doms, Dunne, and Troske [1997] show that U. S. manufacturing plants utilizing more advanced technologies employ more educated workers. Berman, Bound, and Griliches [1994]

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together, have prompted a widely noted conjecture that technological progress and skill have always been relative complements.[3] Even though physical capital and more advanced technologies are now regarded as the relative complements of human capital, were they so in the more distant past?

Some answers have already been provided. A literature on the bias to technological change across history challenges the view that physical and human capital were relative complements throughout the industrial past. Many of the major technological advances of the nineteenth century, according to this literature, substituted physical capital, raw materials, and unskilled labor, as a group, for highly skilled artisans.[4] Rather than being the relative complement to skill, physical capital was, for some time, a relative complement of raw materials and, together with unskilled labor, substituted for highly skilled individuals [Cain and Paterson 1986; James and Skinner 1985].[5] The prototypical

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conclude that the shift in relative labor demand from unskilled (production) to skilled (nonproduction) workers within U. S. manufacturing industries in recent decades has been positively associated with the rate of growth of the capital-output ratio and with the level of investment in R&D and computers. Berndt, Morrison, and Rosenblum [1992] reach similar conclusions. Autor, Katz, and Krueger [1997] find a substantial and growing wage premium associated with computer use despite large increases in the supply of workers with computer skills (see also Krueger, [1993]). Autor, Katz, and Krueger also find greater shifts toward college-educated workers in industries with more rapid growth in computer usage and computer capital per worker. Fallon and Layard [1975] present evidence consistent with capital-skill complementarity using cross-country data at both the aggregate and sectoral levels. Positive correlations have also been found between the utilization of formal company training, and technological change and sectoral capital intensity [Bartel and Sicherman 1995; Mincer 1989].

[3] By skill we mean higher levels of education, ability, or job training. When we use the term technology-skill or capital-skill complementarity, we mean that skilled or more-educated labor is more complementary with new technology or physical capital than is unskilled or less-educated labor.

[4] The term "artisan" is used in this paper to mean a worker who produces virtually the entire good in a production process containing almost no division of labor.

[5] James and Skinner [1985] divide industries in 1850 into two categories: "skilled" (e.g., woodworking) and "unskilled" (e.g., clothing). They find that in both "skilled" and "unskilled" industries raw materials were the relative complements of physical capital, although the effect was greater in the "skilled" sector. More importantly for the capital-skill complementarity hypothesis is that skilled labor was the better substitute for capital in its sector than was unskilled labor in its. Thus, an increase in capital (or raw materials) would have decreased the relative demand for skilled labor. Cain and Paterson [1986] do not consider skill differences but find, analogous to James and Skinner, that capital and raw materials were relative complements and that both together substituted for labor. In the same vein, Abramovitz and David [1973, 1996] characterize the bias to technological change in general as shifting from Harrod labor-saving (capital-deepening) in the nineteenth century to "unconventional-capital" deepening in the twentieth century. Williamson and Lindert [1980], however, assume capital-skill complementarity and generate, in their C.G.E. model, rising inequality with capital-deepening during the nineteenth century.

example is gun making. Cheap lumber in America fostered the use of wood lathes and displaced hand fitting in the production of gun stocks by skilled woodworkers [Hounshell 1984]. The butcher, baker, glassblower, shoemaker, and smith were also skilled artisans whose occupations were profoundly altered by the factory system, machinery, and mechanization.[6]

If technological advance and human skill were not relative complements in the distant past but are today, when did they become so? We argue that technology-skill complementarity emerged in manufacturing early in the twentieth century as particular technologies, known as batch and continuous-process methods of production, spread. The switch to electricity from steam and water-power energy sources was reinforcing because it reduced the demand for unskilled manual workers in many hauling, conveying, and assembly tasks.

We postulate that manufacturing production, for certain products, began in artisanal shops, then shifted to factories (1830s to 1880s), to assembly lines (early 1900s), and more recently to robotized assembly lines.[7] For other types of goods, however, the shift may have been from artisanal shops or factories to continuous- and batch-process methods (1890s and beyond).[8] The production process shifts did not affect all goods similarly, and some were never manufactured by more than one method. But manufacturing as a whole progressed in the fashion we posit: from artisanal shops, to factories (also assembly lines), and then to continuous-process (also robotized assembly-line) or batch methods.

We have in mind rather distinct notions for each process, following a rich literature in the histories of technology and business. The distinction between the artisanal shop and factory

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[6] According to Sokoloff [1986], some initial deskilling, for example in shoemaking, involved little capital, and no mechanization. It was, rather, of the Smithian pin-factory variety. Landes [1972] takes an opposing view. Braverman [1974], among others, argues that industrialization and mechanization served to deskill a host of artisanal trades and to reduce the relative earnings of craftsmen.

[7] See Atack [1987] and Sokoloff [1984] on the transition from the artisanal shop to the factory in the nineteenth century. Both make the important point that the transition was slow in some industries and depended not just on technological change in manufacturing (often in the organization of work) but also on decreases in transport costs. In some industries (e.g., boots and shoes, clothing, furniture, leather, meatpacking, tobacco) a significant minority of value added was produced in artisanal shops (<7 employees with no power source) even as late as 1870. And in some (e.g., saddlery), the majority of value added came from artisanal shops in 1870.

[8] The term "batch" refers here to production "in a batch," generally used for liquids (e.g., liquors), semisolid liquids (e.g., oleomargarine), or molten metals (e.g., steel, aluminum). It is not to be confused with another usage, the production of items in batches (e.g., clothing pieces) for later assembly.

is mainly in the degree of division of labor. Factories are larger, with more specialized workers and often more capital per worker. Batch operations are used for processing liquid, semisolid, or gaseous matters (e.g., chemicals, liquors, dairy products, molten metals, wood pulp). Continuous-process methods, pioneered in the late nineteenth century, are used for products requiring little assembly and having few or no moving parts, such as oats, flour, canned foods (e.g., condensed milk, soup), soap, film, paper, matches, and cigarettes. Continuous-process and batch methods (e.g., Bonsack's cigarette machine, Fourdrinier papermaking machine) are "black-box" technologies, precursors of modern robotized assembly lines. Raw materials are fed in, and finished products emerge, with few hands intervening in production. A corps of machinists and mechanics, however, attend the machinery. Assembly lines, including their robotized versions, generally produce goods constructed from solid components. Note, however, that assembly lines differ in important ways from continuous-process (and batch) methods. Assembly lines, with their vast quantities of human operatives, are the fully rationalized versions of the factory, with its extreme division of labor.

Few products went through all the stages we describe, but those that did are illuminating. Automobile production began in large artisanal shops. Like the carriages that preceded them, automobiles were first assembled by craftsmen who hand-fitted the various pieces.[9] Technological advances then led to standardized and completely interchangeable parts that were assembled in factories, later equipped with assembly lines as at Ford in 1913, by scores of less-skilled workers. Much later, the robotized assembly line appeared using relatively fewer less-skilled operatives and more skilled machine-crewmen. In the history of automobile production, the first technological advances reduced the relative demand for skilled labor, whereas later advances increased it.

The question we address is how these technological shifts affected the relative demand for skill. The transition from the artisanal shop to factory production probably increased the capital-output ratio, but most likely decreased the demand for skilled relative to unskilled labor in manufacturing. The technological advances that later shifted production from the factory (or assembly line) to continuous-process methods further raised the capital-output ratio but also served to increase the relative

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[9] Braverman [1974, p. 146] quotes Eli Chinoy: "Final assembly, for example, had originally been a highly skilled job. Each car was put together in one spot by a number of all-around mechanics." See also Hounshell [1984].

demand for skilled labor. Reinforcing these technological shifts was electrification, the adoption of unit-drive systems, and the automation of hauling and conveying operations which decreased the demand for "common laborers."[10]

Our central point is that the technological shift from factories to continuous-process and batch methods, and from steam and water power to electricity, may have been at the root of an increase in the relative demand for skilled labor in manufacturing in the early twentieth century.[11] We explore the origins of the transition to technology-skill complementarity, believed to be in full blossom today.[12]

We begin with a formal statement of our framework and the conditions under which the technological changes we have in mind will increase the relative demand for skill. We emphasize that our model applies to manufacturing and that our evidence is also primarily confined to that sector. Manufacturing employed 32.4 percent of the nonagricultural labor force in 1910 and 29.1 percent in 1940 [U. S. Department of Commerce 1975, series D152–166]. The sector, moreover, affords the measurement of inputs, outputs, and technological change over a long period.

Our framework predicts that industries adopting advanced technologies (e.g., continuous-process and batch methods) in the first part of this century should have employed production workers with higher average skills and a larger share of nonproduction (white-collar) workers. They should have been more capital-intensive and relied on purchased electricity for a larger share of their horsepower. We assess these predictions using the earliest available national data on the educational levels of workers by industry (viz., the 1940 U. S. census of population) and data on the characteristics of detailed industries (from the 1909, 1919, and 1929 censuses of manufactures).

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[10] Jerome [1934] illustrates this point for many industries. By "unit-drive" we mean separate electric motors for each machine.

[11] Our emphasis here is on the manufacturing sector. Reinforcing the shift in manufacturing was an increased demand for educated labor to sell, install, and service technologically advanced products. In the past ten years individuals who sell computer software and hardware have changed from nerds to slick sales personnel. Similarly, in the early 1920s those who sold radios had to deal with the "radio nuts," those who built their own radios. Not much later, radio sales personnel were hired to increase sales, not fraternize with the wireless amateurs [Electrical Merchandising 1922].

[12] A walk through most any factory today—one that assembles autos or their parts, makes high-grade steel, or fabricates just about anything except clothing—will reveal few production operatives but many capital-maintenance workers. In one auto assembly plant we visited, an engineer proudly reported that any human welder we saw would soon be replaced by robots.

We document substantial differences in the education levels of blue-collar production workers by industry in 1940 that cannot be attributed to the geographic distribution of production. Industries in 1909, 1919, and 1929 with more-skilled blue-collar workers (proxied by contemporaneous mean wages for production workers and education levels for blue-collar workers by industry in 1940) had more capital per worker and used purchased electricity to power a greater fraction of their horsepower. Many of the industries our data reveal to be capital-intensive and high-education have been classified elsewhere as using continuous-process and batch methods [Chandler 1977]. We also examine within-industry changes from 1909 to 1919 and find a positive relationship between changes in capital-intensity and purchased electricity utilization, on the one hand, and the wage-bill share of white-collar workers, on the other.

Overall, the evidence we present from both across- and within-industry analyses of data for 1909 to 1940 is consistent with the notion that the transition from the factory to continuous-processes increased the relative demand for skilled workers. The previous transition, from the artisanal shop to the factory, appears to have involved an opposite force. Many industries that remained artisanal (e.g., engraving, jewelry, clocks and watches) had far lower capital intensity but higher worker skill (education) than the majority that shifted to factory production.

I. A FRAMEWORK TO UNDERSTAND TECHNOLOGY-SKILL COMPLEMENTARITY

In considering our argument, that shifts between production processes change the relative demand for skill, it is useful to envision manufacturing as having two distinct stages: a machine-installation and maintenance segment (termed "machine-maintenance") and a production or assembly portion (termed "production"). The two stages together comprise "manufacturing." Capital and skilled (educated) labor, we will argue, are *always* complements in the machine-maintenance segment of manufacturing for any technology. Machinists, for example, are needed to install machinery and make it run.[13] The "workable" machines created by

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[13] Machine-maintenance may itself have a life-cycle: "In the first stages of such mechanization when machines are somewhat crude, their operation requires the watchful care of skilled machinists. Likewise, to make those improvements which increase machine efficiency, competent machinists are employed to observe

skilled labor and raw capital are then used by unskilled labor to create the final product in the production or assembly segment of manufacturing.

The adoption of a particular technology may increase or decrease the capital to output ratio. Whether or not its adoption increases or decreases the relative demand for skilled workers will depend on the degree to which the demand for skilled labor in machine-maintenance is offset by the demand for unskilled labor in production. We outline a more formal framework showing that the transition from the artisanal shop to the factory probably increased the capital-output ratio but decreased the demand for skilled relative to unskilled labor. The shift from the factory to continuous-process (or batch) methods, however, raised the capital-output ratio and increased the relative demand for skilled labor. But within *any* technology (artisanal, factory, continuous-process) an increase in the ratio of unskilled to skilled wages will *always* induce an increase in the capital-output ratio, the capital-labor ratio, and the relative employment of skilled labor.

Our framework posits three technologies (one with two phases): the artisanal shop or hand production (H), the factory (F) which has a technologically advanced stage called the assembly line (A), and continuous-process or batch (C) methods.[14] There are three inputs: raw (or physical) capital (K), skilled or educated labor (L_s), and unskilled labor (L_u), with corresponding prices r, w_s, and w_u. The manufacturing process contains two distinct segments: (1) raw capital must be installed and maintained, ("machine maintenance") and (2) goods must be assembled or created ("production"). All workers in the "production" segment are unskilled, whereas all workers in "machine-maintenance" are skilled. The machine-maintenance portion is Leontief, and, thus, physical capital and human capital are *always* strict complements in the creation of usable, workable machines for all technologies (H, F or A, and C). The usable, workable machines are K^*.[15] The

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the machines in operation under practical working conditions. But, as machines increase in importance, they must be further improved in efficiency so as to require little attention and a minimum number of stoppages for repairs or overhauling. This increasing efficiency of the machine itself tends, in the long run, to eliminate much of the work of that large corps of machinists which was required when machines were first installed to displace hand workers" [Anderson and Davidson 1940, p. 228].

[14] As we noted before, one can also include the robotized assembly line in this last group.

[15] We also assume, realistically, that K^* cannot be shifted from one technology to another but is specific to the technology for which it was created.

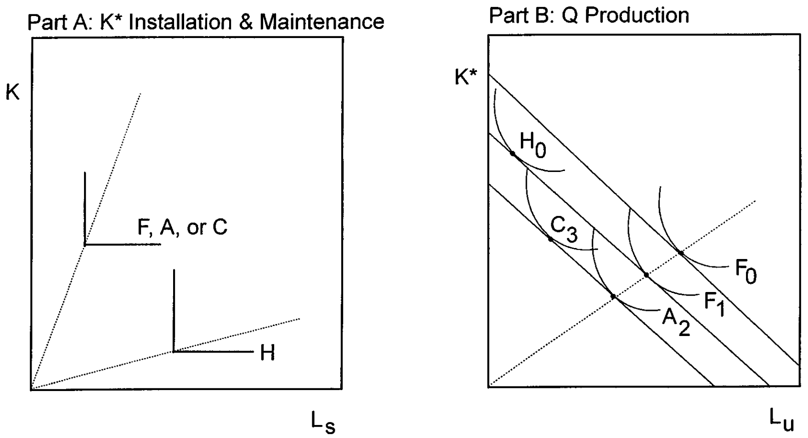

FIGURE I
A Simple Framework for Understanding the Relationships among Capital, Technology, and Skill

production portion of manufacturing uses K^* and L_u to manufacture Q and is Cobb-Douglas. Thus, the creation of K^* is a separable part of Q production.[16]

The various technologies differ in straightforward and relatively intuitive ways. Consider first the differences in the creation of K^*. Factories and continuous-process methods do not necessarily require different ratios of skilled labor to capital to create workable machines, but the artisanal shop, in which each artisan maintains his own tools, has a higher ratio. Thus, we assume that the same factor proportions are needed to create K^* in the F (or A) and C technologies, but that the H technology requires a larger amount of L_s relative to K (as in Figure I, Part A). In the production of Q, however, each of the technologies requires a different ratio of unskilled labor to workable capital. The greatest

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[16] Our framework produces results that are qualitatively similar to those of a more general production function such as a two-level CES of the form,

$$Q = A_i[\alpha_i(K^*)^{\rho_i} + (1 - \alpha_i)L_u^{\rho_i}]^{1/\rho_i} \qquad \rho_i \leq 1$$

$$K^* = [\beta_i(K)^{\theta_i} + (1 - \beta_i)\, L_s^{\theta_i}]^{1/\theta_i} \qquad \theta_i \leq 1$$

as long as $\rho_i > \theta_i$ for $i = H, F, A, C$. We analyze the special case for which $\rho_i = 0$ and $\theta_i = -\infty$.

is in the factory (and assembly line), the next is for continuous-process methods, and the least is in the artisanal shop, which used little unskilled labor. Thus, production of Q using the H technology is the most intensive in K^*, next is C, and last is F (or A), as in Figure I, Part B.[17] More formally, we assume that K^* is generated by

$$(1) \qquad K^* = \min(\lambda_i^1 \cdot L_s, \lambda_i^k \cdot K) \qquad i = H, F, A, C$$

such that $\lambda_{F,A,C}^1 > \lambda_H^1$, and $\lambda_{F,A,C}^k < \lambda_H^k$, where $1/\lambda_i^1$, for example, is the unit skilled-labor requirement for K^* creation in production process i. Q production is, likewise, given by

$$(2) \qquad Q = \gamma_i \cdot (L_u)^{\alpha_i} (K^*)^{(1-\alpha_i)} \qquad i = H, F, A, C$$

such that $\alpha_H < \alpha_C < \alpha_{F,A}$.

Even though skilled labor and capital are strictly complements in machine-maintenance for all technologies, as in equation (1), a change in technology (meaning production process) need not increase the relative demand for skilled labor.[18] The reason can be seen with reference to Figure I (see also Table I). Part B of Figure I is drawn so that all isoquants represent equal amounts of Q. It has also been drawn for a very special case of K^* production, one in which the average cost of K^* for all technologies is the same (and thus for which all isocost lines in part B are parallel). If r_i^* is the average cost of K^* for technology i, the condition for which r^* is equal for the H and F (or A or C) technologies is

$$(3) \qquad r/w^s = [(\lambda_F^1)^{-1} - (\lambda_H^1)^{-1}]/[(\lambda_H^k)^{-1} - (\lambda_F^k)^{-1}].$$

That condition, although not necessary for our results, makes the

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[17] Our schematic representation of manufacturing as consisting of two related stages, machine maintenance and production, is easily applied to the factory, assembly-line, and continuous-process methods. But it makes the least sense for the artisanal shop because artisans are involved in both processes. For our schematic representation to make sense for the artisanal shop, it must be that the machine-maintenance segment includes some production and that the production segment finishes the product. In the manufacture of window-glass, which remained artisanal into the early twentieth century, an artisan would maintain his capital and blow the "cylinder." Less-skilled workmen would then cut the cylinder and make window-glass from it. Even though all window-glass was made by hand in 1900, only 44 percent was in 1914; the industry had been transformed by a new "factory" technology of rolled glass [Jerome 1934, p. 101].

[18] By a technological advance from artisanal production to the factory system, we mean an increase in γ_F relative to γ_H. The appearance of continuous or batch processes, likewise, comes from an increase in γ_C relative to γ_F.

TABLE I

PREDICTIONS OF THE FRAMEWORK

Technological change	K/Q	$K/(L_s + L_u)$	$L_s/(L_s + L_u)$
(a) Shift from artisanal or hand trades (H) to factory production (F)	↑[a]	?[b]	↓[c]
(b) Shift from factory (F) to assembly-line (A) production (Hicks-neutral technical change)	↓	→	→
(c) Shift from assembly-line (A) to continuous-process (or batch) methods (C)	↑	↑	↑

K = capital stock.

L_s = skilled or more-educated labor.

L_u = unskilled or less-educated labor.

[a] The prediction is obtained when $(\lambda_F^k/\lambda_H^k) < [(1-\alpha_F)/(1-\alpha_H)] \cdot (r_H^*/r_F^*)$. That is, considering the restrictive case discussed in the text of equal r^* for H and F, the prediction is correct only if the higher K^*-intensity for the H technology is outweighed by the greater use of K in the creation of K^* in the F technology.

[b] The impact of (a) on $[K/(L_s + L_u)]$ is ambiguous in the case when $[L_s/(L_s + L_u)]$ declines.

[c] The prediction holds in the restrictive case of equal r^* for H and F. When the r^*s differ, the condition is $(r_H^*/r_F^*) < [(\alpha_F/\alpha_H)] \cdot [(1-\alpha_H)/(1-\alpha_F)] \cdot (\lambda_F^1/\lambda_H^1)$.

geometry far simpler.[19] Without it we will need a less restrictive condition for one of the results.

Consider the factory system to be in its infancy in period 0, at which time continuous processes will not have been invented and the artisanal shop is the dominant mode of production. We begin, therefore, at point H_0 with production taking place only in the artisanal shop. Note that just because K^* is relatively high at H_0 does not mean that much *raw* capital per unit of output is used. As can be seen in Part A of Figure I, and as per equation (1), the H technology uses relatively more L_s than do the other technologies in producing K^*.

Technological change makes the factory system a rival mode of Q production, as can be seen from a Hicks-neutral technical change that shifts F_0 to F_1 (resulting from an increase in γ_F). As this type of technological change proceeds, firms will eventually switch from the H to the F technology. The shift from artisanal shops to factories initially causes an increase in (K/Q), in (K/L_s), probably also in $K/(L_s + L_u)$, and a decrease in $L_s/(L_s + L_u)$.[20] In the more general case of our framework, in which the isocost lines

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[19] If the r^*s were different, the isocost lines would not be parallel. The condition simply states that the degree to which the cost of a unit of K exceeds that for a unit of L_s must equal the degree to which F conserves on L_s, relative to H, compared with how much H conserves on K, relative to F.

[20] See Table I for the various conditions. We are considering here a small factor-neutral technological change around F_1. Greater technological change, as in the movement to A, can decrease K/Q.

in Part B are not parallel for the H and F technologies, a weaker condition than that given by equation (3) is required for the conclusion that a shift to the factory system increases the relative demand for unskilled labor. The condition requires that the share of unskilled labor in total product be sufficiently larger for the factory technology than it is for the artisanal shop technology. It is likely that such a condition held.[21]

Additional Hicks-neutral technical change shifts the F isoquant to A_2 through an organizational innovation: the assembly line. The shift does not change the capital-labor ratio nor the relative demand for skilled labor, but it does lower the capital-output ratio.

The shift of most interest to us is that to continuous-process methods, given by isoquant C_3.[22] Although its machine-maintenance technology is identical to that of the A or F processes, continuous-process methods have a higher output elasticity with respect to K^* than do the A or F processes ($\alpha_C < \alpha_{F,A}$). That is, C conserves on (unskilled) labor in the production segment and thus uses K^* more intensively. The shift from the A or F technologies to C increases (K/Q), $K/(L_s + L_u)$, and $L_s/(L_s + L_u)$. With the adoption of C we observe capital-skill complementarity and technology-skill complementarity, at *given* factor prices, in the sense that the shift to a more advanced technology is associated with increases in both capital intensity and the relative employment of more-skilled workers.[23]

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[21] More formally, the condition is that $(r_H^*/\ r_F^*) < (\alpha_F/\alpha_H)\cdot[(1 - \alpha_H)/(1 - \alpha_F)]\cdot(\lambda_F^1/\lambda_H^1)$. Intuitively, the condition for the shift from H to F to decrease the relative demand for skilled labor, given Q, will not occur if (r_H^*/r_F^*) is too high. The cost of installed capital will be relatively high in the H sector when the cost of skilled labor is great in comparison with raw capital. When that occurs, the H sector will have an incentive to conserve on expensive K^* in the production of Q, by substituting unskilled labor for K^*. But the condition will hold, even when (r_H^*/r_F^*) is high, if α_H is sufficiently low in comparison with α_F. The shift to the F technology will, then, still increase the relative demand for unskilled labor because the marginal product of L_u is lower in the H technology (given Q and L_u). The effect is further helped by the assumption that $\lambda_F^1 > \lambda_H^1$. It does seem reasonable that, for given Q and L_u, the marginal product of unskilled labor was lower in the artisanal shop mode of production compared with the factory. After all, the reason for having the factory system, with its more intricate division of labor, was to increase the marginal product of unskilled labor.

[22] The shift from A to C could result from technological advance (growth in γ_C relative to $\gamma_{A,F}$) or to an increase in the relative price of unskilled labor (increase in w_u/r^*), as occurred with the expansion of high schools after 1910 [Goldin 1998] and the reduction of immigration after 1914 [Goldin and Katz 1995].

[23] Although we do not have a fourth input—raw materials—it is easy to compare our framework with that in James and Skinner [1984]. Their skilled sector is our artisanal sector, and it shifts from the H to the F technology, thereby increasing K/Q, probably also K/L, but decreasing the fraction of the workforce

The increased reliance on electricity as a source of horsepower and the introduction of unit-drive appears to have had effects similar to the movement to continuous-process methods. The mechanization of the hauling and conveying of materials decreased the relative demand for unskilled labor and increased capital intensity, and the faster and hotter running of machinery powered by electric motors required relatively more machine-maintenance personnel.[24]

In summary, the role played by skilled labor in machine-maintenance means that capital and skilled labor are relative complements within any given manufacturing production process. But capital and skilled workers may be relative complements or substitutes in shifts among different manufacturing processes depending on the nature of the technological change. The movement from artisanal production to factories in the nineteenth century involved the substitution of capital and unskilled labor for skilled (artisanal) labor. The adoption of continuous-process and unit-drive methods in the twentieth century involved the substitution of capital and skilled (educated) labor for unskilled labor.

A complementary hypothesis, advanced by Greenwood and Yorukoglu [1997], is that all technological change increases the relative demand for skilled labor, who facilitate the adoption of new technologies. We, instead, emphasize the skill-biased or unskilled-biased nature of distinct technological innovations rather than simply the rate of technological change. Thus, we argue that the deskilling involved in the transition from artisanal to factory production offset the need for more flexible workers who assisted in the introduction of factory methods. The observed evolution of relative wages, employment, and wage bill shares by education and occupation throughout the twentieth century would appear to require a rapid and persistent secular growth in the relative demand for more-educated workers [Goldin and Katz 1995; Autor, Katz, and Krueger 1997; Johnson 1997]. The skill-biased nature of electrification and computerization, as emphasized by our

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that is skilled. The cause of the technological shift in their case is the lower relative price of raw materials in the United States versus Britain.

[24] According to Jerome [1934, pp. 402–403]: "The construction, installation, repair, maintenance, and adjustment of machines . . . is requiring an ever-increasing army of relatively skilled men. . . . On the whole the shift will continue to be from the emphasis on the trade skill typical of the handicraftsman to, on the one hand, the alertness and intelligence required in handling fast and intricate machinery and, on the other, to the more formal training required in the engineering and production planning departments."

framework, is consistent with the continuing rise in the relative demand for more-skilled workers within manufacturing.

II. TECHNOLOGY-SKILL AND CAPITAL-SKILL COMPLEMENTARITY: 1909 TO 1940

We turn now to the historical record to observe when technology, capital, and skill became relative complements in the U. S. manufacturing sector. Ideally we would use plant-level data on the nature of technology and worker skills. But because such data are not available for our period, we examine, instead, industry-level measures of technology indicators (capital intensity and purchased electricity use) and utilize proxies for worker skills (education levels, occupational mix, and wages).

Our framework predicts that industries farther along in the transition from the factory to continuous-process methods should have employed production workers with higher average skill levels (e.g., machinists) and a larger share of white-collar workers. They should have been more capital-intensive and used purchased-electricity for more of their horsepower. We assess these predictions using both cross-sectional comparisons between industries and panel data on the determinants of differences in the rate of within-industry changes in the relative utilization of skilled labor.

Various measurement issues arise in our study (see also the Data Appendix). Our primary sources for technology indicators and workforce information by detailed (approximately four-digit) industry are the U. S. censuses of manufactures for 1909, 1919, and 1929. Information on purchased electricity usage is available in 1909, 1919, and 1929, but data on the capital stock are only available for 1909 and 1919.[25] The censuses of manufactures provide data on employment and total (wage and salary) expenses for broad occupational categories (all wage earners and various categories of nonproduction workers).[26] The data, however, are

[25] Capital was also inquired of in 1914, but the question on the capital stock ended in 1919. In 1939 a question was asked on capital investment. For a discussion of the accuracy and consistency of the capital stock variable, and in its defense, see Creamer, Dobrovolosky, and Borenstein [1960, Appendix A]. Capital was to include only the owned portions of land, buildings, machinery, tools, inventories, and working capital (e.g., cash) and to be assessed at book value.

[26] The groups enumerated for nonproduction workers are proprietors and firm members; salaried officers; superintendents, managers, engineers, and other technical experts; and clerks, stenographers, salesmen, and other salaried employees.

not disaggregated into subgroups of blue-collar workers, except by sex and broad age categories, and no direct evidence is given on the average skill or education of workers by industry and occupation. But beginning in 1940 the U. S. census of population asked highest grade completed, industry, and occupation.[27] The 1940 population census allows us to identify industries that used disproportionate numbers of higher-educated (e.g., high school graduate) workers in blue-collar occupations, and the census of manufactures can reveal whether these high-education industries were more capital- or electricity-intensive from 1909 to 1929.

A. Educated Labor in Blue-Collar Occupations

It is generally believed that production workers in manufacturing for much of the twentieth century were less educated than average and did not vary much in their formal education by industry (e.g., Nelson and Wright [1992]). After all, for much of the early part of this century most would have been foreign born or the children of the foreign born. There is some truth to these claims. But that with which we take issue is that production workers in manufacturing were an undifferentiated group with respect to their formal education. In fact, we will show, using the 1940 population census, that there were wide differences by industry in the educational attainment of blue-collar manufacturing workers and that these differences were directly related to industry characteristics.

We limit the analysis of the 1940 data to 18 to 34-years old men in blue-collar occupations (craft, operatives, laborers, service) working in the manufacturing sector.[28] The age limitation is imposed because the educational attainment reported by older Americans in the 1940 census appears overstated. Among all 18- to 34-year old, male blue-collar manufacturing workers in the 1940 PUMS (Public Use Microdata Sample), 27.6 percent stated they completed twelve years or more of schooling, most of whom were graduates of high schools.[29] As a fraction of the total

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[27] 27. The 1940 U. S. population census was the first U. S. decennial census to ask educational attainment. Only three state censuses did so prior to 1940 (Iowa 1915, 1925; South Dakota 1915).

[28] 28. Our substantive findings are similar if we look, instead, at the educational attainment of all workers, all male workers or at all blue-collar workers, rather than restrict attention, as we do, to 18 to 34-year old blue-collar males.

[29] 29. The sample is restricted to the currently employed. In 1940 more than 10 percent of those in the labor force were unemployed, and another 4 percent were on work-relief. For some reasons why the 1940 census overstates the educational attainment of older Americans, see Goldin [1998].

blue-collar workforce, the more-educated were disproportionately found in particular industries. The industries, moreover, fit the categorization we offered previously, for many used continuous-process and batch technologies (petroleum refining, dairy products, paints and varnishes, nonferrous metals) or were high-technology industries and those producing recently innovated goods (aircraft, business machinery, scientific and photographic equipment).[30]

We list, in Table II, industries by the percentage of their blue-collar male workers (18 to 34-years old) who were high school graduates, giving those in the top and bottom 20 percent by employment.[31] The industries divide into two main categories. At the low end of the education spectrum are the products of the first industrial revolution as well as those used in construction: cotton, woolen, and silk textiles, boots and shoes, lumber, stone, clay, and cement. At the high end are certain products of the second industrial revolution (e.g., chemicals, petroleum), many in the machine-producing group, and some crafted in settings similar to the artisanal shop (i.e., clocks, watches, jewelry, and even aircraft). Finally, there is that perennial among high-education industries: printing and publishing.[32]

Before making further sense of the findings regarding high- and low-education industries, we must address whether the results are generated by geographic differences in both education and industry or by age differences in employment and educational attainment. We have regressed an indicator variable for high school graduation (twelve or more years of schooling) on a full set of age, state, metropolitan status, and industry dummies using

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[30] The list would probably include many others in the batch and continuous-process group if the 1940 census tabulated finer categories of industries, e.g., distilled liquors, pharmaceuticals. Industries are defined as high-technology if a large percentage of their total labor force were engineers, chemists, and other scientific personnel similar to currently used definitions.

[31] The 1940 PUMS separately identifies 61 manufacturing industries that, for the most part, correspond to current three-digit SIC industries and some of the larger four-digit industries.

[32] The results differ trivially if years of education instead of the percentage graduating from high school were used. In addition, sectors other than manufacturing display similar patterns. More educated blue-collar workers in the communications, transportation, and public utilities sectors were found in telephone, wire and radio, air transportation, petroleum and gasoline pipe lines, electric light and power, and radio broadcasting and television. In retail trade new products and those that were time-sensitive or more valuable per unit were sold, delivered, and serviced by high school graduates. For example, drivers for jewelry stores and drugstores were more educated than were other drivers. Blue-collar workers in radio stores, and even gas-station attendants, were far more educated than the average blue-collar worker.

TABLE II

PERCENTAGE HIGH SCHOOL GRADUATES BY INDUSTRY, 18 TO 34-YEAR OLD MALE BLUE-COLLAR WORKERS: 1940

Three-digit SIC manufacturing industries	*% H.S. grad.*	*Number of obs.*	*Three-digit SIC manufacturing industries*	*% H.S. grad.*	*Number of obs.*
High-education industries (from high to low) *Top 20% by employment*			*Low-education industries (from low to high)* *Bottom 20% by employment*		
Aircraft and parts	52.7	541	Cotton manufactures	10.8	1512
Printing and publishing	44.7	1289	Tobacco	11.6	144
Office machinery	43.7	166	Logging	11.7	706
Petroleum refining	43.3	415	Sawmills and planing mills	14.1	1941
Dairy products	43.2	417	Not specified textile mills	15.6	128
Scientific and photographic equipment	40.8	227	Silk and rayon manufactures	16.6	350
Electrical machinery	40.5	977	Carpets and rugs	16.9	107
Misc. nonmetallic mineral products	36.2	135	Misc. fabricated textiles	17.0	94
Paints and varnishes	35.9	107	Cut-stone and stone products	17.1	101
Clocks, watches, jewelry	34.7	197	Misc. textile goods	17.6	117
Shipbuilding	34.4	528	Structural clay products	18.8	271
Miscellaneous machinery	33.5	1669	Cement and concrete, gypsum, and plaster products	19.2	263
Nonferrous metals	33.1	342	Hats, except cloth and millinery	20.5	60
			Dyeing and finishing textiles	20.6	191
			Misc. wooden goods	21.4	475
			Footwear industries except rubber	22.9	680
			Woolens and worsteds	23.1	368

The sample is limited to 18 to 34-year old, currently employed males in blue-collar occupations (craft, operative, laborer, service) in manufacturing. The mean for the entire sample of 31,531 is 27.6 percent. The industry names are those given in ICPSR [1984]. High-education (low-education) industries are obtained by ranking industries by their share of 18 to 34-year old, male, blue-collar workers with twelve or more years of schooling and selecting off industries from the top (bottom) until 20 percent of manufacturing employment (for all workers) is represented. The 1940 PUMS sampling weights are used in all calculations.

Source. 1940 Public Use Micro-data Sample, 1/100; ICPSR [1984].

our sample of young male, blue-collar manufacturing workers from the 1940 PUMS. The estimated coefficients on the industry dummy variables can be viewed as industry differences in blue-collar educational attainment adjusted for differences in urbanization, the regional distribution of production, and age. A more extreme adjustment uses the mean industry residuals from the analogous regression, excluding the industry dummies. The adjusted industry coefficients and the mean industry residuals retain an almost identical set of rankings to that of the raw data presented in Table II. Furthermore, the differences in educational attainment of blue-collar workers across industries are substantial even after adjusting for differences in urbanization, regional location of production, and age structure. The standard deviation of the actual share of high school graduates among young male blue-collar workers across manufacturing industries is 0.086 as compared with 0.080 for the adjusted industry coefficients and 0.071 for the mean industry residuals.

Another possibility is that the distribution of educated workers by industry in 1940 was a product of the Depression. Firms that employed high-educated workers, according to this logic, would, in the face of decreased demand, have fired low-educated workers and replaced them with their higher-skilled employees. Such occupational changes are well documented for the Depression years. But even in 1950 and 1960, most of the high-education industries and sectors we identify in 1940 remained high-education. Our categorization is not simply a product of the Depression.

We have established that, in 1940, firms in particular industries hired disproportionate numbers of educated blue-collar workers. The high- and low-education industries in Table II appear to fit the prediction of the framework that high-technology, continuous-process, batch-process, and artisanal modes of production should use more skilled production workers than the factory processes of the first industrial revolution.[33] Our framework also

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[33] Data on employment by detailed (four-digit) industries from the 1909 to 1929 Censuses of Manufactures indicate that the majority of employees in five 1940 census industry categories (beverages, dairy products, grain-mill product, paints and varnishes and petroleum refining) worked in industries classified by Chandler [1977] as using continuous-process or batch-production methods. Consistent with our framework, these industries employed a disproportionate share of more-educated blue-collar workers in 1940: 36.0 percent of young, blue-collar workers in these continuous-process and batch production industries had twelve or more years of schooling as compared with 27.1 percent in the remainder of manufacturing.

suggests that industries with more educated blue-collar workers should also have more skilled workforces overall as proxied by a greater utilization of white-collar workers. In fact, there is a strong positive correlation between the education level (share with twelve or more years of schooling) of blue-collar workers and the white-collar share of total employment across manufacturing industries in 1940: the unweighted correlation is 0.61 and the employment-weighted correlation is 0.73 for the 61 manufacturing industries separately enumerated in the 1940 PUMS.

To investigate more directly capital-skill and technology-skill complementarity in the 1909 to 1940 period, we have merged the education data by industry from the 1940 population census with that on industry attributes from the 1909, 1919, and 1929 censuses of manufactures. The industry categories in the 1940 population census are far broader than those in the censuses of manufactures, and we have aggregated the earlier data to conform to the 1940 categories for our analysis of the determinants of industry variation in education levels (see the Data Appendix). Table III presents regressions of the educational level of 18 to 34-year old male blue-collar workers in 1940 (adjusted for differences in age composition, urbanization, and geographic distribution of employment) on the capital to labor ratio (in 1909 and 1919), a measure of horsepower electrification (averaged over 1909, 1919, and 1929), and various controls for worker and industry characteristics.[34]

The ratio of capital to wage-earners in 1909 and 1919 is positively related to the education of workers by industry in 1940 (see Table III, columns (1) and (2)), and the effect is economically significant. Increasing the capital to labor ratio by the equivalent of its difference between, for example, the lumber and timber and oleomargarine industries in 1909 increases the high school graduation rate by seven percentage points or by 25 percent in 1940.[35] Thus, more capital-intensive industries employed a more highly educated labor force some twenty years later.

We find similar effects with respect to the use of purchased electricity, entered either as the fraction of horsepower that was

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[34] The results are quite similar when we use the actual high school graduate share of 18 to 34-year old, blue-collar males (unadjusted for differences in age composition and geography) as the dependent variable.

[35] These industries were chosen because oleomargarine production used a continuous-process technology, whereas lumber and timber was mainly factory produced. (Capital/wage-earners) in lumber and timber was $1693, and was $5871 in oleomargarine in 1909.

TABLE III
EDUCATION, CAPITAL INTENSITY, AND ELECTRICITY USAGE, 1909 AND 1919

	Adjusted fraction high school graduates among 18 to 34-year old males in blue-collar occupations, by industry			
	Capital intensity		*Capital and electrification*	
	(1) *1909*	*(2)* *1919*	*(3)* *1919*	*(4)* *1919*
log (K/L)	.0589	.0496	.0632	.0592
	(.0169)	(.0202)	(.0194)	(.0205)
% hp purchased electricity			.199	
			(.0531)	
log (hp purchased electricity/L)				.0359
				(.0151)
log (other horsepower/L)				−.0405
				(.0088)
log (total horsepower/L)			−.0043	
			(.0149)	
d log (employment)$_{1909,1929}$			.0313	.0311
			(.0126)	(.0128)
% artisan	.187	.189	.118	.122
	(.0336)	(.0355)	(.0295)	(.0295)
% female	.142	.0932	−.0442	.0086
	(.0537)	(.0524)	(.0636)	(.0652)
% children	−1.56	−1.56	−.660	−.804
	(.490)	(.515)	(.463)	(.487)
Constant	.203	.193	.0921	.185
	(.0238)	(.0361)	(.0366)	(.0307)
Number of observations	57	57	57	57
R^2	.482	.428	.711	.703

Standard errors are in parentheses. The unit of observation is a 1940-industry group. Industries from the 1909, 1919, and 1929 Censuses of Manufactures are aggregated up to the 1940 groupings, e.g., beverages in 1940 contains the 1909 categories of distilled, malt, and vinous liquors, and mineral and soda waters. Each observation is weighted by the industry share of total blue-collar employment in manufacturing averaged over 1909, 1919, and 1929. The dependent variable is the adjusted percentage of 18 to 34-year old, male blue-collar workers in the industry in 1940 who graduated high school. The "adjustment" is as follows. A regression of an indicator variable for high school graduation (twelve or more years of schooling) on a full set of state dummies, year-of-age dummies, indicator variables for central city and metropolitan area residence, and a full set of three-digit 1940 census industry dummies was run on all employed 18 to 34-year old, male blue-collar workers in the manufacturing, communications, transportation, and utilities sectors in the 1940 PUMS (sample size = 38,940, weighted by the 1940 PUMS sampling weights). The coefficient on each of the 57 industry dummies is the adjusted high school graduate share of young, male blue-collar workers for each 1940 industry.

log (K/L) = log of capital stock (000, in current dollars) per wage earner in each industry for 1909 and 1919, respectively, as indicated by the column headings.

% hp purchased electricity = fraction total horsepower run by purchased electricity, averaged over 1909, 1919, and 1929.

log (hp purchased electricity/L) = log of the horsepower of motors run by purchased electricity per wage earner averaged over 1909, 1919, and 1929.

log (other horsepower/L) = log of total horsepower of prime movers per wage earner averaged over 1909, 1919, and 1929; the total horsepower of prime movers includes the horsepower of steam engines, steam turbines, water wheels, internal combustion engines, and so on.

log (total horsepower/L) = log of total horsepower of prime movers + the horsepower of motors run by purchased electricity per wage earner averaged over 1909, 1919, and 1929.

d log (employment)$_{1909,1929}$ = change in log of total employment from 1909 to 1929.

% artisan = fraction of wage earners in the 1940 industry categories who were in a disaggregated industry (in 1909, 1919, 1929) classified as an artisanal trade, averaged over 1909, 1919, and 1929. Artisan is defined as working in: gold and silver, leaf and foil; jewelry; photo-engraving; stereotyping and electrotyping; cardcut design; wood and die engraving; glass; glass-cutting, staining and ornamenting; instruments; optical goods; and statuary art. Printing and publishing is also included because of its special feature of demanding a literate labor force.

% female = average fraction of wage earners female in 1909, 1919, and 1929.

% child = average fraction of wage earners child in 1909 and 1919.

Sources. U. S. Department of Commerce, Bureau of the Census [1913, 1923, 1933] supplemented with data provided by Arthur Woolf. See Woolf [1980].

1940 Public-Use Microdata Sample, 1/100; ICPSR [1984].

run by purchased electricity or as the log of the electricity variable per wage earner (columns (3) and (4)). The effect, moreover, is obtained even when the growth of industry employment from 1909 to 1929 is held constant. Production-worker skill was related not just to industry growth and the resulting newness of plant and equipment. Rather, the usage of purchased electricity affected the relative demand for skill independent of industry growth. An 18 percentage point increase in the purchased electricity share of horsepower (a one-standard-deviation change) is associated with a 3.6 percentage point increase in the share of young blue-collar workers who were high school graduates. Note that increases in total horsepower did not have the same effect. The type of power, not simply its amount, affected the skill level.

Electricity use in manufacturing grew rapidly during the 1909 to 1929 period. The percentage of all horsepower in manufacturing driven by electric motors was 23 percent in 1909 but soared to 77 percent by 1929 [Du Boff 1979]. Electric power was both purchased from power plants and generated by firms using their prime-movers (e.g., steam engines). Motors powered by purchased electricity grew the fastest of the two, from 9 percent of all horsepower in 1909 to 53 percent in 1929. Even though the growth of purchased electricity was greater than that of all electricity, generated electricity was still a sizable fraction of all horsepower in 1929 (24 percent). For various reasons, the measurement of horsepower driven by generated electricity is imprecise. Using the best estimates provided for the two types, we find a much greater impact on education levels from purchased electricity.[36]

There are many potential reasons for these findings, but no hard evidence. One possibility is that purchased electricity was associated with larger changes in the machinery of the factory than was generated electricity. Electricity and separate motors (unit-drive) enabled many industries to automate conveying and hauling operations and thereby eliminate substantial numbers of common laborers. Many industries were prompted to introduce labor-saving methods with the onset of World War I, and chief among them were iron and steel, brick manufacturing, pottery, Portland cement, pulp and paper, rubber tires and tubes, slaugh-

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[36] 36. The generated electricity variable is estimated using the procedure described in Du Boff [1979, Appendix A], although see Jerome [1934] for another method. The problem is that motors powered by generated electricity are often rated above their actual use, which is limited by the horsepower of the prime movers, whereas those powered by purchased electricity can be run at or above their rating.

tering and meatpacking, lumber manufacture and woodworking, and mining [Jerome 1934; Nelson 1987; Nye 1990].[37] Ample and cheap electricity rendered feasible the production of various materials, such as aluminum and other electrochemicals, that disproportionately used skilled labor. Cheap electricity also encouraged a more intensive use of machines thereby increasing demand for the skilled personnel who maintained them.[38] But purchased electricity may also have been associated simply with newer factories and technological advances built into a newer capital stock.[39]

Note that we do not mean to imply that there was any direct relationship between the individual workers in 1909 (or 1919) and 1940. In fact, education levels in Table III refer to men 18 to 34-years old in 1940 who could not have been in the 1909 labor force. We are claiming, however, that there is something about these industries that increased the value of secondary-school education during the 1909 to 1940 period.

Secondary schooling spread rapidly after 1910. Less than 10 percent of youths had high school diplomas in 1910, but by the mid-1920s to mid-1930s 30 percent to 50 percent did, depending

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[37] In iron and steel "the proportion of common laborers was cut approximately in half from 1910 to 1931. The evidence is unmistakable," notes Jerome, "that recent progress has eliminated unskilled labor to a much greater extent than other grades" [1934, p. 63]. In all these industries, the use of conveyors, traveling cranes, jitneys, carriers, industrial trucks, and other handling devices reduced the relative demand for unskilled labor. The changes, moreover, were evident as early as 1916 to 1920. We find, from the 1910 and 1940 PUMS of the census of population, that laborers as a share of total manufacturing employment declined from 23.6 percent in 1910 to 14.3 percent in 1940 [ICPSR 1984, 1989].

[38] Electricity played a complex role in increasing the relative demand for skilled workers. Although Nye [1990, pp. 234–235] concludes that electricity increased the relative demand for skill, he also describes opposite effects. "As the electrified factory evolved it required a different mix of labor and management . . . more middle management; more engineers and technicians; fewer artisanal workers; and a more complex grading of worker skills, with many more semiskilled laborers . . . and far fewer unskilled workers. . . . Boy mule drivers in coal mines, carriers in tire factories, or shovelers of raw materials in steel mills saw their work taken over by electric locomotives, conveyors, and cranes . . . as a few skilled men using expensive machines did work formerly performed by a mass of the unskilled." The increase in purchased electricity use, moreover, decreased the need for prime movers and the skilled labor that serviced them. See also Du Boff [1979] and Devine [1983] on the transition from mechanical to electric drive and the introduction of group and unit drive motors.

[39] The adjustment in Table III for the growth of the industry will account for some of this factor. The newness of the capital stock concerns the replacement of the shafts and pulleys of the older system of power with separate machines (unit-drive) associated with electricity. Note that either generated or purchased electricity could have accomplished the same transformation. Data on the average horsepower of motors suggest that firms with purchased electricity switched more completely to unit-drive (smaller motors), whereas those generating their own appear to have used group-drive more.

on region (see Goldin [1998] and Goldin and Katz [1997]). The increase in formal education expanded the supply of skilled manufacturing workers and altered their training. Before the spread of high schools, most skilled machine-maintenance occupations (e.g., machinist, electrician, technician) had cognitive skills (e.g., algebra, geometry, trigonometry, mechanical drawing) learned on-the-job by reasonably able individuals. These skills were precisely those taught to young people in high schools. Formal education substituted for a combination of ability and job training, and the expansion of secondary schooling greatly increased the supply of skilled manufacturing workers.

Were these more-educated blue-collar employees paid commensurately more? The earliest nationally representative sample with data on earnings and education is the 1940 PUMS, which contains earnings data for 1939. We estimate, using the 1940 PUMS, that the "rate of return" to a year of schooling was 8.3 percent, in a standard human capital (log) earnings equation for young, male blue-collar workers (white, 18 to 34-years old). The return for a similar group of ordinary white-collar workers was 8.9 percent.[40] The coefficient on years of schooling is .065 (*s.e.* .0012) for our young, male blue-collar sample in an expanded (log) earnings equation including a full set of industry dummies, potential experience, and its square. Thus, the positive earnings differential for more-educated blue-collar workers in 1939 arose both because they ended up in higher-wage industries and because they earned a substantial educational wage premium within industries.

The average blue-collar wage in 1909, 1919, and 1929 is also strongly and positively related to the education level of the industry's blue-collar workers in 1940. The coefficient on years of schooling is 12 percent in 1909, 10 percent in 1919, and 17.5 percent in 1929 in regressions presented in Table IV of the (log) average wage in each year on average years of schooling among blue-collar workers in 1940. Although it is tempting to interpret the coefficient on years of schooling as the rate of return to an

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[40] The coefficient on years of schooling for the blue-collar sample is .083 (*s.e.* .0013) in a log (full-time equivalent) weekly earnings equation that includes potential-experience and its square. The analogous regression for young, male, ordinary white-collar workers (white, 18–34 years old, sales and clerical occupations) in manufacturing is .091 (*s.e.* .0028). The blue-collar and ordinary white-collar samples contain 27,942 and 4,892 observations, respectively. The estimated return in the blue-collar sample is 7 percent when a full set of state dummies are also included.

TABLE IV

RELATIONSHIP BETWEEN EARNINGS (1909, 1919, 1929) AND EDUCATION (1940) FOR 18 TO 34-YEAR OLD BLUE-COLLAR MALES, BY INDUSTRY

	Log (average annual, current $, wage) in 1909, 1919, or 1929 industry		
	1909	*1919*	*1929*
Average years schooling among blue-collar, 18 to 34-year old males in 1940 industry grouping	.125 (.0111)	.0995 (.0128)	.176 (.0190)
Percentage (women + children) among wage earners in 1909 or 1919 industry; percentage female in 1929 industry	−.494 (.0681)	−.605 (.111)	−.497 (.0917)
Constant	5.21 (.102)	6.24 (.114)	5.63 (.184)
Number of observations	191	191	191
Weighted mean of dependent variable	6.24	7.00	7.13
R^2	.699	.644	.657
$\hat{\sigma}$	.117	.133	.151

The number of 1940 industries is less than the number of 1909, 1919, or 1929 industries. Regressions are weighted by the number of wage-earners in each 1909, 1919, 1929 industry. Numbers in parentheses are Huber (White) standard errors allowing for grouped errors within 1940 industries. The education variable (average number of years of school) is from the 1940 PUMS. The average wage is computed as the wage bill/(average annual number of wage earners) for all years.

Source: U. S. Department of Commerce, Bureau of the Census [1913, 1923, 1933] supplemented with data provided by Arthur Woolf. See Woolf [1980].

1940 Public Use Micro-data Sample, 1/100; ICPSR [1984].

individual's education, it is, instead, a combination of that and the return to working in an industry having more educated workers. Using data sets containing more complete information, such as the censuses beginning with 1940, one can reconstruct the "poorer" data we are forced to use and measure both the individual and industry effects. Almost identical magnitudes are obtained to those we present for 1929 even though the return to an individual's years of education is far less.[41] In light of these comparisons we interpret the coefficients for 1909 to 1929 as

[41] We construct a similar regression using micro-level data from the 1940 PUMS by aggregating across industries. The analogous regression of the log(average wage, production workers) by industry on average years of schooling of male blue-collar workers, 18 to 34-years old, in that industry (and the percentage female of blue-collar workers) yields a coefficient of .185 (*s.e.* .013). In contrast, a micro-level regression of individual log(earnings) on own schooling (plus a female dummy) yields a coefficient of .040 (*s.e.* .0004). Because an experience variable is not included, the coefficient on education is lower than in regressions that estimate the return to education.

indicating that a return to education for blue-collar jobs existed, but we are not certain of its magnitude.[42]

More direct evidence on the relationship between earnings and education of blue-collar workers comes from a sample we have collected from the Iowa state census of 1915, a unique set of documents containing information on years of schooling, type of schooling, annual earnings, and occupation (see Goldin and Katz [1998]). Although industry information is not available, we can identify nonfarm, blue-collar workers (laborers, operatives, and craft workers). The coefficient on years of schooling in a log (annual) earnings regression containing potential experience and its square and an urban area dummy is .087 (*s.e.* .0045) for 18 to 34-year old, nonfarm, white male blue-collar workers in 1915. When we separate years of education by type of schooling (common school, grammar school, high school, and college), the coefficient increases to .116 (*s.e.* .0093) for years of high school.[43] Thus, the evidence from several sources indicates employers apparently valued the education of blue-collar workers in the 1909 to 1939 period.

Educational attainment provides a useful proxy for the skill levels of production workers, but it does not fully capture skill differences related to on-the-job training, apprenticeship training, and other sources. Earnings provide another (indirect) summary measure that may capture all aspects of worker skill rewarded by employers. The data on average earnings of blue-collar workers by industry from the census of manufactures for 1909, 1919, and 1929 allow us to look at contemporaneous correlations of an indicator of skills and industry characteristics. In Table V we explore the relationship between average earnings per wage earner and the capital and electricity variables in 1909, 1919, and 1929.[44] We find, consistent with the previous results, a positive relationship between the ratio of capital to labor and wages and, similarly, a positive correlation between wages and the percent-

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[42] The wage regressions in Table IV (and those in Table V) use consistent data on average annual earnings of blue-collar workers by industry for 1909, 1919, and 1929. Because hours of work may have varied in a manner that could bias the results, we have also estimated these regressions (for 1909 and 1919) using hourly earnings, where hours worked in each industry is estimated from a distribution of hours. The results are robust to the choice of hourly or annual data.

[43] Our sample of 18 to 34-year old, white, male, nonfarm, blue-collar workers for Iowa in 1915 contains 3021 observations. The mean of schooling in this sample is 8.05 years, and 15.7 percent attended some high school.

[44] We use the 1919 ratios of capital to labor for 1929.

TABLE V
RELATIONSHIP BETWEEN PRODUCTION-WORKER EARNINGS AND INDUSTRY CHARACTERISTICS, 1909, 1919, 1929

	Log (average annual, current $, wage) in 1909, 1919, or 1929 industry			
	1909 (s.e.)	*1919 (s.e.)*	*1929 (s.e.)*	*Means, 1929 (s.d.)*
log (*K*/*L*)	.0910	.0417	.0480	1.44
	(.0151)	(.0169)	(.0262)	(.510)
% hp purchased electricity	.439	.266	.546	.637
	(.0556)	(.0374)	(.0548)	(.211)
log (total horsepower/*L*)	−.0213	−.00149	.0184	1.09
	(.0115)	(.0131)	(.0189)	(1.07)
log (employment/number of establishments)	.0622	.0780	.0638	4.51
	(.00633)	(.00577)	(.0103)	(1.08)
% female	−.427	−.308	−.307	.210
	(.0563)	(.0613)	(.0881)	(.225)
% child	−3.41	−6.91	−6.41	.014
	(.377)	(.697)	(.927)	(.016)
Artisan	.136	.144	.273	.0563
	(.0338)	(.0336)	(.0481)	(.231)
Constant	5.99	6.65	6.56	
	(.0306)	(.0386)	(.0666)	
Number of observations	228	225	228	
Mean of weighted dependent variable	6.23	7.03	7.15	
R^2	.791	.813	.667	
$\hat{\sigma}$	.0991	.0973	.148	

The average wage is computed as the (production-worker wage bill)/(average annual number of wage earners) for all years. Independent variables are defined in Table III. Log (*K*/*L*) by industry for 1919 is used in the 1929 regression; % child for 1919 is used in the 1929 regression. Regressions are weighted by the number of wage earners in each year, as are the means for 1929.

Source. U. S. Department of Commerce, Bureau of the Census [1913, 1923, 1933] supplemented with data provided by Arthur Woolf. See Woolf [1980].

age of all horsepower from purchased electricity.[45] Because World War I caused a transitory compression in production-worker wages, we prefer to concentrate on the 1909 and 1929 coefficients. The magnitudes implied by the coefficients are substantial, particularly with regard to purchased electricity use. The differ-

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[45] Within-industry variation over the 1909 to 1929 period leads to similar conclusions to the between-industry regressions reported in Table V. There are positive and significant relationships between the change in the (log) average earnings of production workers from 1909 to 1929 and changes in capital intensity and electricity use (conditional on controls for changes in the other covariates included in the Table V regressions).

ence, for example, between the capital to labor ratios in the oleomargarine and lumber and timber industries implies a 5 percent premium in wages for oleomargarine; the difference in their purchased electricity use implies a 23 percent wage difference.[46] The wage premiums we measure are largely due, we believe, to compositional effects; a greater proportion of educated workers was found in industries with more capital per worker and more industry horsepower coming from purchased electricity.[47]

That high school graduate blue-collar workers were employed in particular industries (more capital-intensive, using a greater fraction of horsepower run by electricity, often producing newer goods) and were paid substantially more, may come as a surprise. Rarely is the education of production workers mentioned in the labor history literature. Yet there is qualitative evidence, complementing our empirical findings, that cognitive skills were highly valued in various trades. High school graduates were sought because they could read manuals and blueprints, knew about chemistry and electricity, could do algebra and solve formulas, and, we surmise, could more effectively converse with nonproduction workers in high-technology industries. Blue-collar positions requiring some years of high school or a diploma were described as needing cognitive skills such as “good judgment,” “skilled in free-hand drawing,” “special ability to interpret drawings,” “[familiarity] with the chemical formulas,” “general knowledge of chemicals used,” “[ability] to mix the chemicals.” More technical skills were also valued such as “knowledge of electricity” and “of electric wire sizes and insulation,” “technical knowledge of the properties of glass,” “general knowledge of photography.” Printing establishments required that beginners be “well versed in grammar, spelling, punctuation,” and noted that “an elementary knowledge

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[46] The wage premiums use the 1929 coefficients. The actual difference in wages is 33 percent. Oleomargarine had a capital to labor ratio in 1919 of $8759 and 69.4 percent of its horsepower came from purchased electricity; the numbers for lumber and timber are $3028 and 27.5 percent.

[47] Another interpretation is that the wage differentials reflect premiums for identically skilled individuals working in more capital- and electricity-intensive industries in which there was greater worker bargaining power and managerial discretion (e.g., Slichter [1950]). That may well be the case. But the strong correlation between wages in the 1909 to 1929 period and education in 1940, by industry, provides evidence that the compositional effect matters. There is, as well, a relationship between the high-education industries given in Table II and the percentage of the industry’s 1910 labor force that was “machine related” (e.g., machinist, electrician).

of Latin and Greek is helpful."[48] High school educated youths were hired into skilled occupations, but they were also sought for ordinary positions in many of the "high-education" industries.

B. Technology-Skill Complementarity and Nonproduction Workers

The relative size of the nonproduction (white-collar) group provides an alternative proxy for skill levels. A larger nonproduction worker share of employment is likely to be associated with an increase in the average amount of skill required of all workers, both because white-collar jobs tend to have higher education requirements and because technical nonproduction workers (engineers and chemists) tend to work with more-educated production workers [Allen 1996]. Continuous-process and batch methods required more managerial and professional employees, relative to production workers [Chandler 1977], and our estimations above provide evidence that such processes also required relatively more skilled blue-collar workers.

The data from the census of manufactures for 1909 and 1919 allow a further assessment of the importance of technology-skill complementarity early in this century by examining whether the relative utilization of nonproduction workers increased with capital intensity and reliance on purchased electricity.[49] Cross-industry comparisons for both 1909 and 1919 indicate robust and strong positive partial correlations between the nonproduction worker share of employment (or labor costs) and both the (log) capital to labor ratio and the fraction of horsepower from purchased electricity (in regressions analogous to those in Table V including controls for log horsepower per worker, demographics, and other industry characteristics).

We next examine whether within-industry changes in capital intensity and purchased electricity usage generate similar patterns. The approach allows a direct comparison with results using more recent data. Various studies have demonstrated a positive relationship between skill upgrading and both advanced technol-

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[48] See, for example, the descriptions of positions in electrical machinery, glass, medicinal manufacturing, paint and varnish, and the printing trades in U. S. Department of Labor [various years, 1918–1921].

[49] Chiswick [1979] addresses a somewhat different question using cross-state aggregate manufacturing data for both 1909 and 1919 and fails to find much evidence of aggregate capital-skill complementarity (where skilled workers are salaried officers and managers). Our data are for the same years, but are disaggregated by industry. In addition, we analyze the composition of skill demand within detailed industries in which all nonproduction workers (including clerical workers) are in the skilled group.

ogy indicators (computer usage, computer investment, R&D intensity) and the growth of the capital to output ratio [Berman, Bound, and Griliches 1994; Autor, Katz, and Krueger 1997]. The precise estimating equation is motivated by a model in which capital, over each ten-year horizon, is the quasi-fixed factor and nonproduction (skilled or educated) and production (unskilled) labor are the variable factors.[50] If the variable cost function (total labor cost function) for industry j is translog and production exhibits constant returns to scale, then cost minimization produces an equation for the nonproduction labor share of total labor costs (S) in time t of the form,

$$(4) \qquad S_{jt} = \alpha_j + \phi_j t + \gamma_i \ln (w_n/w_p)_{jt} + \rho_j \ln (K/Q)_{jt},$$

where w_n (w_p) is the wage of nonproduction (production) workers, (K/Q) is the capital to output ratio, and ϕ_j measures the rate of skill-biased technological change in industry j. Differencing equation (4) to eliminate industry fixed-effects, yields the following estimating equation for the change in the nonproduction share of the wage bill in industry j (under the assumptions that γ_j and ρ_j do not vary across industries or, more realistically, that the average coefficients across industries are being estimated):

$$(5) \qquad dS_{jt} = \beta_0 + \beta_1\, d\ln (w_n/w_p)_{jt} + \beta_2\, d\ln (K/Q)_{jt} + \epsilon_{jt}.$$

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. The condition $\beta_2 > 0$ implies capital-skill complementarity; β_0 captures the cross-industry average of the skill-bias to technical change and $(\beta_0 + \epsilon_{jt})$ is the industry-specific bias to technical change plus measurement error. The intuitive interpretation of $\beta_2 > 0$ is that when capital and skilled labor are relative complements, industries experiencing a greater increase in capital intensity are those with a larger increase in the nonproduction worker share of total labor costs.

We estimate equation (5) as well as a modification that drops the relative wage variable, because cross-sectional wage variation could largely reflect skill differences, not exogenous wage varia-

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[50] See Berman, Bound, and Griliches [1994] and Brown and Christensen [1981].

tion.[51] The data are matched at the (pseudo) four-digit SIC industry level—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 (often including professionals), and clericals (often including other salaried workers). Their share of manufacturing employment increased from 13.9 percent in 1909 to 15.7 percent in 1919. Among the data issues we had to confront are the treatment of proprietor earnings and the choice of output and capital deflators.[52] In some industries (e.g., bakeries), proprietors were a large fraction of all workers and probably performed managerial and clerical duties. We have chosen to exclude their income from the wage bill.[53] Our input (capital) and output (shipments; value added, viz., shipments minus materials cost) variables are both nominal measures. In the absence of industry-specific output prices and materials and investment deflators, we use the aggregate WPI for the 1909 to 1919 period.[54]

The results for 1909 to 1919, in Table VI, reveal that the coefficient on the change in the (log) capital-output ratio (β_2) is consistently positive and significant regardless of other controls and independent of the output measure (shipments or value added).[55] Inclusion of the change in the relative wage reduces the coefficient somewhat, but far less so when we purge the wage differential of certain compositional effects.[56] We also find that the

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[51] We also add an output term to account for cyclical differences in the extent to which nonproduction and production labor are quasi-fixed factors. This also allows the production function to be nonhomothetic.

[52] The weighting of the regression is another data issue. Because classification errors are more of a problem for small industries, we weight by the wage bill share. Qualitatively similar results obtain without weights, and median regressions without weights also yield similar results.

[53] Two methods of accounting for proprietor earnings can be offered: one imputes their earnings as if they earned the average nonproduction wage in the census, and the second assumes that proprietor income entirely reflects returns to capital and should not be included in the overall wage bill (it was not supposed to be included). We present the results under the latter assumption; they are robust to either.

[54] We have tested the sensitivity of applying industry-specific versus aggregate deflators using data from the NBER Manufacturing Productivity Database for 1959 to 1989 and find that the capital-skill complementarity coefficient (β_2) is robust to the choice of deflator.

[55] Qualitatively similar results are obtained by using the employment share of nonproduction workers as the dependent variable. We prefer the cost share measure because it implicitly adjusts for changes in relative labor quality and hours of work.

[56] To mitigate the influence of compositional effects on changes in the sectoral skill premiums, we use the clerical wage for the nonproduction workers and adjust the change in the skill premium for changes in percent female and child labor among production workers (see column (7) of Table VI).

inclusion of a measure of technological advance—the change in the percentage of horsepower run by purchased electricity—does not greatly affect the coefficient on $d\ln(K/Q)$ and is itself positive and significant.

How large we interpret the effects in Table VI to be will depend on their magnitude more recently, when many have concluded on the basis of such regressions that there is capital-skill complementarity. We present such a comparison in Table VII. The first two columns repeat the results from columns (1) and (2) in Table VI. The remaining six give as identical as possible estimations using quite similar four-digit industry data from the NBER Productivity Manufacturing Database for 1959–1969, 1969–

TABLE VI

CHANGE IN THE NONPRODUCTION-WORKER SHARE OF WAGE BILL, 1909 TO 1919

Variable	*(1)*	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*
$d\ln(K/Q)$	.059	.051			.044		.054	.048
	(.011)	(.012)			(.010)		(.010)	(.012)
$d\ln(Q)$		−.008						−.013
		(.004)						(.005)
$d\ln(K/VA)$			.051	.042		.032		
			(.010)	(.011)		(.010)		
$d\ln(VA)$				−.0080				
				(.0044)				
$d\ln(w_n/w_p)$					.094	.092		
					(.013)	(.014)		
$d\ln(w_c/w_p)$							.099	
							(.014)	
d(% electrified)								.046
								(.020)
Constant	.017	.018	.016	.017	.034	.032	.016	.008
	(.003)	(.003)	(.003)	(.003)	(.004)	(.004)	(.003)	(.005)
R^2	.100	.111	.093	.105	.248	.227	.247	.108
$\hat{\sigma}$	.0367	.0366	.0368	.0366	.0336	.0340	.0336	.0357

The dependent variable is the change in the nonproduction-worker share of the wage bill between 1909 and 1919. The number of observations is 256 for columns (1)–(7) and 253 for column (8). An observation is an industry, generally at the (pseudo for 1909 and 1919) four-digit SIC level. Regressions are weighted by the average wage bill share between 1909 and 1919. Standard errors are in parentheses. The weighted mean of the dependent variable is 0.006.

K = capital stock.

Q = value of products (or shipments).

VA = value added.

w_n = average wage of nonproduction workers.

w_p = average wage of production workers.

w_c = average wage of clerical workers.

$d\ln(w_c/w_p)$ = change in the (log) wage of clerical and productive workers adjusted for the change in the percentage female and percentage child workers of production workers.

d(% electrified) = change in the fraction of total horsepower run by purchased electricity.

Sources. U. S. Department of Commerce, Bureau of the Census [1913, 1923].

TABLE VII

CHANGE IN NONPRODUCTION-WORKER SHARE OF WAGE BILL: 1909–1919, 1959–1969, 1969–1979, 1979–1989

	1909–1919		*1959–1969*		*1969–1979*		*1979–1989*	
Variable	*(1)*	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*
$d\ln (K/Q)$	.059	.051	.005	.018	.023	.040	.024	.061
	(.011)	(.012)	(.005)	(.006)	(.006)	(.009)	(.008)	(.011)
$d\ln (Q)$		−.008		.026		.021		.036
		(.004)		(.006)		(.008)		(.007)
Constant	.017	.018	.010	−.003	.010	.005	.037	.030
	(.003)	(.003)	(.002)	(.004)	(.002)	(.003)	(.002)	(.002)
R^2	.100	.111	.002	.040	.026	.040	.018	.071
$\hat{\sigma}$	.0367	.0366	.0354	.0348	.0415	.0412	.0438	.0427
Number of observations	256	256	450	450	450	450	450	450
Mean of weighted dependent variable	.006	.006	.011	.011	.013	.013	.037	.037

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 are weighted by the average wage bill share between the years given. Standard errors are in parentheses. Nominal quantities are deflated by the WPI for 1909–1919 and by the PPI for finished goods in the other three periods.

K = capital stock.

Q = shipments.

Sources. U. S. Department of Commerce, Bureau of the Census [1913, 1923] for 1909–1919 data. NBER Manufacturing Productivity Database, derived from the Annual Survey of Manufactures, as described in Bartelsman and Gray [1996], for 1959 to 1989 data. Deflators. 1909, 1919: U. S. Department of Commerce, Bureau of the Census [1975], series E-40. All other years: *Economic Report of the President* [1995], Table B-64, p. 347.

1979, and 1979–1989.[57] The striking finding is that the coefficient on the change in the (log) capital-output ratio (β_2) is larger for the 1909–1919 period than more recently. Only one coefficient—that for 1979–1989 in the estimation with the change in shipments variable—is larger. The comparison of the results for 1909–1919 with those more recently suggests a strong movement during the 1910s toward capital-skill complementarity.

III. TECHNOLOGY-SKILL COMPLEMENTARITY: HISTORICAL INSIGHTS AND CONCLUSION

We began with the notion, garnered from various sources, that many technological advances of the nineteenth century

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[57] For consistency with the data from 1909 to 1919, the aggregate PPI for finished goods is used to deflate all nominal quantities in the 1959 to 1989 comparison period.

increased the relative demand for the lesser-skilled in manufacturing but that studies using recent data generally find the reverse. Capital and skills, and technology and skills, are deemed relative complements today. Our goal was to locate the origins, and thus the sources, of technology-skill and capital-skill complementarity in manufacturing. We have demonstrated that such relative complementarities existed from 1909 to 1929 and were associated with technologies, such as continuous-process and batch methods, and with the adoption of electric motors.[58] To motivate the empirical work, we devised a framework in which capital is always a relative complement of skilled labor in the creation of workable machines but in which unskilled labor is used with machines to create output. Manufacturing-wide capital-skill complementarity arises from a shift *between* particular technologies. Our evidence has pertained mainly to the period since 1909 and to the transition from the factory (or assembly-line) system to continuous-process and batch methods and electric motors in manufacturing.

One often hears that we are living in a time of extraordinary technological change. Yet the technologies that appeared or diffused in the two decades around 1915 may have been more consequential. Manufacturing horsepower in the form of purchased electricity rose from 9 percent in 1909 to 53 percent in 1929; similar changes swept residential use. New goods proliferated: automobiles, airplanes, commercial radio, aluminum, synthetic dyes, and rayon; household electric appliances (e.g., refrigerators and washing machines); office machinery (e.g., calculators, dictating machines, and copying equipment). New techniques improved the production of rubber, plate glass, gasoline, canned condensed milk, and factory-made butter. Of the goods mentioned all but the auto are among the higher-education industries we identify for 1940 and which appear also to have been the higher-skill industries in the 1910s and 1920s. Looking back at Table II, the high-education industries include aircraft, office and store machines, petroleum refining, dairy products, electrical

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[58] Using similar data from the 1890 census of manufactures, we have also found a positive relationship between the ratio of capital to labor and production worker wages, and a positive correlation between the growth of the nonproduction worker wage share and capital's share from 1890 to 1909. Thus, the origins of capital-skill and technology-skill complementarity may have been earlier than we discuss here, consistent with Chandler's [1977] dating of the beginnings of continuous-process and batch methods.

machinery, paints and varnishes, miscellaneous machinery, and nonferrous metals.

Input price changes may have been reinforcing in enticing firms to adopt particular technologies. The decline in the price of purchased electricity was the greatest change and perhaps most significant.[59] Cheaper power, purchased electricity, and unit-drive meant that firms could adopt different types of capital and production processes.[60] Although the advent of electric utilities, and thus purchased electricity, meant that less capital was needed to generate power within firms, production-capital (as opposed to power-generating capital) could run faster and hotter, thereby requiring greater numbers of skilled workers to maintain it.

The technologically forward industries of the day also grew the fastest. If we define a high-education industry (see Table II) as one in which more than 33 percent of the young male blue-collar workers had a high school degree in 1940, the share of manufacturing employment in these industries rose from 20.7 percent in 1909 to 26.7 percent in 1929. The share in low-education industries (defined as less than 23 percent with high school degrees in 1940) declined from 29.0 percent in 1909 to 20.5 percent in 1929. The share of manufacturing employment in the top five (two-digit) industries by education (petroleum, chemicals, electrical machinery, printing and publishing, and scientific instruments) continued to expand from 10 percent to 16 percent over the 1910 to 1940 period [Goldin and Katz 1995, Table A4].[61] Similar shifts have occurred more recently, reinforcing the effects of capital- and technology-skill complementarity.

If, according to our estimates, there was as much skill-biased technical change in the manufacturing sector from 1909 to 1929

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[59] According to Woolf [1980, Table 2.1], nominal price declines for electricity were 3.4 percent, and real declines exceeded 5 percent average annually from 1910 to 1929.

[60] See Du Boff [1979] and Devine [1983] on why unit-drive (separate motors for each tool) diffused slowly until the 1920s. Before electricity, mechanized firms were powered by prime movers, and the power was often distributed throughout the factory by a complex series of shafts and pulleys. Electricity and small motors enabled firms to replace this system with one that was cleaner and safer, and in which tools were more efficiently arranged. But large capital investments were tied up in the previous arrangement.

[61] Within-industry skill upgrading associated with the adoption of new technologies was probably a more important source of increases in the relative demand for skill than were shifts of employment between industries. For example, the nonproduction worker wage bill share grew from 21.5 percent in 1909 to 23.6 percent in 1929. Of that change, we find, using our matched sample of industries from the 1909 and 1929 Censuses of Manufactures, that approximately two-thirds occurred *within* four-digit industries. This finding is similar to that observed in manufacturing over the past few decades [Berman, Bound, and Griliches 1994].

as more recently, was there also as much widening in the gap between the skilled and the unskilled?[62] We have reported elsewhere that the wages of ordinary white-collar workers fell relative to those for all production workers from the mid-1910s to the early-1920s and then remained at this lower level through 1940 [Goldin and Katz 1995]. Because ordinary white-collar workers in 1910 were mainly high school graduates, the wage differences by occupation are similar to those by education. That is, the wage gap between the high school educated and the less educated first fell and then remained at that level for some time. Rather than widening during a period of skill-biased technical change, the wage gap actually narrowed and then remained stable.

What accounts for the contrast between the labor market response to skill-biased technical change from 1909 to 1940 and today? One potential difference is that the supply of educated workers greatly and rapidly expanded at an increasing rate throughout the earlier period. In thousands of school districts across the United States high schools mushroomed, curricula modernized, and enrollments soared from 1910 to 1940 [Goldin 1998; Goldin and Katz 1997]. The vast majority of those who graduated high school in the 1910s but did not continue to college, entered a host of ordinary white-collar occupations, such as clerks, bookkeepers, secretaries, and various sales positions. The large premium to high school educated workers that existed at the turn of the century, and which may have prompted the high school expansion, was markedly reduced by the 1920s, although it remained substantial. A once-expensive commodity—a high school graduate—suddenly became a more reasonably priced input and this change in relative input prices may have further fueled skill-biased technical change. Most importantly, as the high

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[62] Note that the impact of skill-biased technical change is potentially even more pervasive. Chandler [1977] notes that the managerial revolution was brought about by many of the technologies we believe increased the relative demand for educated labor on the shop-floor. The demand for more-educated farm workers must also have increased as agricultural machinery became more complex. Goldin and Katz [1995] infer from data on movements in the relative wages of white-collar workers and relative skill supplies (under the assumption of a stable elasticity of substitution between more- and less-skilled workers) that the relative demand for workers with at least a high school degree grew rapidly from 1890 to 1940 in the manufacturing sector and the aggregate economy. In fact, the rate of growth of the (log) relative wage bill share of nonproduction workers in manufacturing (a measure of the growth in the relative demand for nonproduction workers with an elasticity of substitution between nonproduction and production workers of close to one) was almost as large from 1890 to 1929 (.0103 log points per year) as it was in the more recent period of generally acknowledged rapid growth in the relative demand for skills from 1959 to 1989 (.0128 log points per year).

school movement continued to spread across America in the 1920s, the wage gap between the high school educated employee and the less-educated worker may have been kept in check in an era of skill-biased technical change.

DATA APPENDIX

Manufacturing Data 1909, 1919, 1929

The primary source for our data on the manufacturing sector is the U. S. Census of Manufactures for the years 1909, 1919, and 1929. We use U. S. aggregates by industry for the capital stock (1909, 1919 only), wage earners (average number employed over the year), female ($>$15 years) and child ($<$16 years) workers, expenses on all wage earners, employment of various groups of nonproduction workers (proprietors, salaried officials, managers, and clerks), expenses on nonproduction workers (salaries), total employment, number of establishments, value of output, materials expenses, value added, total primary horsepower, horsepower of motors run by purchased electricity, and horsepower from generated electricity, from U. S. Department of Commerce, Bureau of the Census [1913, 1923, 1933]. For 1909 and 1929 we employ a data set generously provided by Arthur Woolf (see Woolf [1980]) for the power variables and some others, and matched the information by industry to our data. We have also constructed a similar data set used in some of our supplemental analyses from the 1890 Census of Manufactures [U. S. Census Office 1895].

The census surveyed establishments (defined as "separate plants operated under the same ownership . . . in different states or counties and for those in different cities having a population of 10,000 or more") and, beginning in 1909, limited its purview to "factories" as opposed to "the neighborhood, hand, and building industries." Establishments with annual gross output of less than $500 were not surveyed in 1909 and 1919, and the cutoff was raised to $5000 in 1929 (see Fabricant [1940] on the absence of biases resulting from the change). The data were averaged by the census at the industry level across the entire United States. A comprehensive standard industrial classification (SIC) system had not yet been established by 1929 and the industries listed in the three censuses are at various levels of aggregation depending on the value of gross output produced. There is, however, considerable overlap from one decade to the next. Because by 1929 the SIC system was being developed (see Beales [1930]), we have useful sources for making concordances across the three census years and also with the 1940 census of population.

The 1909 Census of Manufactures contains information on 260 separate industries. That for 1919 has more detail and lists 354 separate industries, many of which are also tabulated as aggregated industries (e.g., tobacco, cigars, and cigarettes). The Census of Manufactures for 1929 contains data on 326 separate industries. During the period we study some industries emerged (e.g., airplanes in 1919), whereas various smaller ones were later grouped into a miscellaneous category (e.g., wood carpet). Still other industries were separated over time (e.g., iron and steel, processed; iron and steel, steel works and rolling mills), yet others were merged (e.g., beverages). There are 61 manufacturing industries in the 1940 Census of Population PUMS. Most are similar to current three-digit SIC classifications (e.g., beverage industries).

We use various concordance procedures to produce consistent samples that are as large as possible in all the empirical work reported. That for Table III takes the 1909, 1919, and 1929 industries and maps them into 57 of the 61 industrial groups given in the 1940 PUMS. To do so, we relied on U. S. Department of Commerce, Bureau of the Census [1940] to link the 1909, 1919, 1929, and 1940 industries, and the insights of Fabricant [1940] concerning products that underwent change from 1909 to 1940.

The procedure followed for Tables IV and V was to use industries at the same level of aggregation for each of the three years, 1909, 1919, and 1929, although for 1919 three of the industries were dropped due to missing information on purchased electricity. Across the three years (1909, 1919, and 1929) we can match 228 (pseudo) four-digit industries covering 99 percent of manufacturing employment in those years. The census documentation provides detailed information on the relationship among the industries in the three Census of Manufactures; we also consulted Beales [1930]. For Table IV we were able to match 191 of these industries to the industrial groups in the 1940 PUMS.

The concordance used for Tables VI and VII matches 256 of the 260 industries in 1909 to the industries in the 1919 Census of Manufactures, some of which had to be aggregated up to the 1909 categories. Because the 1919 data are given at a more disaggregated level than those for 1909, the concordance was done by mapping the 1919 industries into those for 1909. Three of these matched industries are missing purchased electricity data in 1919.

Manufacturing Data 1959, 1969, 1989

The data on the nonproduction worker share of the wage bill, the capital stock, and shipments for 1959, 1969, and 1989 for 450 four-digit manufacturing industries are from the NBER Manufacturing Productivity Database. Documentation on this database is available in Bartelsman and Gray [1996]. For comparability with the 1909 and 1919 data, we first convert the real capital stock variable available in the NBER Productivity Database for 1959–1989 into a nominal capital stock variable using the industry-specific price deflators for new investment. We then deflate each industry's nominal capital stock by the aggregate PPI for finished goods for 1959 to 1989.

Education and Earnings Data 1940

Data on the education of manufacturing workers in 1940 and the earnings of manufacturing workers in 1939 come from the 1% Public Use Micro-Sample of the 1940 Census of Population [ICPSR 1984]. High school graduates are defined as those with twelve or more years of schooling; years of schooling are given by the highest grade completed. Weekly earnings in 1939 are computed as the ratio of annual wage and salary income to the number of (equivalent full-time) weeks worked. The samples for 1939 earnings regressions are limited to wage and salary employees.

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