Specialization and the Skill Premium in the 20th Century

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Abstract

The skill premium fell substantially in the first part of the 20th century, and then rose at the end of the century. I argue that these changes are connected to the organization of production. When production is organized into large plants, jobs become routinized, favoring less skilled workers. A model is introduced which parameterizes capital's ability to do many tasks, that is, capital's flexibility. Higher flexibility of capital makes optimal plant size smaller and the skill premium higher. When calibrated to data on the distribution of plant sizes, the model can account for between half and two-thirds of the movement in the skill premium over the century. It is also in accord with a variety of industry level evidence.

*I thank Tom Holmes for extensive discussions on the subject.

1 Introduction

During the latter part of the twentieth century, the skill premium rose substantially. The change has prompted a huge literature attempting to explain the change (see Bound and Johnson (1992)). Theories of "skill biased technological change" posit that changes in the skill premium are driven by technological changes. A variety of reasons for skill bias are possible. For instance, following Grilliches (1969), Krusell et al. (2000) consider the possibility of capital-skill complementarity. They use data on the price of equipment for the latter part of the century to show that improved machinery can explain the rising premium if capital is more substitutable with low skilled labor than it is with high skilled labor. Others focus directly on computers and the impact of the information technology revolution on wages (Dunne, et al. (2000)).

There is an important relationship between plant size and the skill premium over the 20th century. During the first half of the century, plant size rose and the skill premium fell. At the end of the century, the skill premium rose as plant size fell. The next section documents the relationship. The exercise in this paper is to develop a model to understand that relationship and see to what extent changes in the skill premium can be explained by such a model.

In the model, a plant is defined by a fixed set of tasks, each of which requires the input of capital and labor. Both inputs pay a fixed cost for each task undertaken. Labor comes in many skill levels. The definition of skilled labor in this paper is that its fixed cost per task is smaller. Whereas skilled labor can easily move from one task to another, unskilled workers can only do tasks that are carefully structured and relatively simple. Adding additional responsibilities is relatively difficult for skilled workers.

As labor inputs become highly specialized, that is, do few tasks, the benefit of skills is reduced. In the assembly line, each worker does such a small set of tasks so that skills are relatively unimportant. Given the assumption about skills, the comparative static exercise is to change the ratio of fixed to marginal costs for capital. The rise of mass production allowed for a larger fixed cost but lower marginal cost (as in Goldin and Katz (1998)); flexible machines of the present make capital more flexible and able to do a wider variety of tasks, so that congestion at the plant can be avoided. When the fixed cost for capital is relatively high, plants are large, workers are very specialized, and the skill premium is low. This is the interpretation of the middle of the century, when plants were larger and the skill premium was low.

Whereas models such as the one in Krusell et al. (2000) focus on an aggregate production function, and are therefore silent on plant size, here many plants will operate with their size determined by the classic U-shaped cost curve arising from a fixed cost followed by a region of decreasing returns. The important novelty of the approach in this paper is that the size of plants is used as a measure of specialization, to infer how much is being undertaken by each worker in each time period. Qualitatively, the model predicts the negative relationship between plant size and the skill premium that is evident in the data. The series on plant size is used to undertake a quantitative exercise, asking how much of the change in the skill premium can be explained in this way. The fixed cost for capital is chosen for each time period so that the model matches the plant size data exactly. Then the model's implied skill premium is compared to the actual one. The model is able to explain between half and two-thirds of the movement in the skill premium.

At the heart of the story is that there is an important difference between the technological change of the first and second halves of the century. During the first half, the spread of mass production led to larger manufacturing plants. Assembly lines replaced the customizable batch production of skilled craft workers. A skilled craftsman at the turn of the century could do a wide variety of tasks needed to complete a given item. On the other hand, a worker on the assembly line has a very routinized, specialized task to perform. Many jobs became routinized, and required little of the skills that once were needed to produce the same product. Because of the focus of the work on repeating a single task, the problem solving skills that allow a worker to do a variety of tasks are not required.

The recent experience of U.S. manufacturing is that flexible, numerically controlled machines have allowed plants to operate at a smaller scale (Milgrom and Roberts (1990)). Production has shifted from the traditional assembly line to batch processes using the new machines, integrated with computers to do a variety of tasks. As a result, workers are no longer as highly specialized in a single routinized task. Each batch is highly customizable, and requires a worker who can manipulate the modern machinery and make it perform a wide variety of tasks depending on the custom features of the batch. As the Fordist factory has given way to smaller customized batches, the set of problems that a worker needs to solve has grown, increasing the demand for skills.

There is cross-sectional evidence at the industry level to support the model's basic premise. Although the dominant force in the first half of the century was the move to mass production with highly specialized jobs, Goldin and Katz (1998) identify industries such as chemical industries which moved to batch process methods during the early part of the period.[1] They show that these industries increased the employment share of skilled workers. In other words, during a period where technological change seemed to be de-skilling on average, industries that moved to more flexible technologies (interpreted here as lower fixed cost of capital) moved to a more skilled workforce.

For the panel of manufacturing industries from 1977-1994, downsizing, in terms of a reduction in average plant size for a given industry, is related to an increase in average industry wages and an increase in productivity growth. This is despite the fact that industries with larger plants pay higher wages overall. The pattern is consistent with the forces outlined in the model: reductions in specialization, as measured by falling plant size, lead to firms employing a more skilled workforce.

One explanation of the falling skill premium in the first half of the century is to turn around the argument in Krusell et al. (2000) and claim that technological change in capital goods was slow during that period. During that period, however, the diffusion of electricity led to new, highly productive technologies (Jovanovic and Rousseau (2000)), contradicting this period as one of technological stagnation in equipment. Moreover, the stock of skilled workers was growing relatively slowly during this period, making it even more of a puzzle that technological progress did not drive up the skill premium. It seems that the technological change of that period was substantial, but "de-skilling." Adding the role of specialization in determining the premium allows this model to explain both periods. Like Krusell et al. (2000), changes in the skill premium are linked to observables, as opposed to computing skill bias as a residual as in, for instance, Bound and Johnson (1992).

Three closely related papers are Mobius (2000), Caselli (1999), and Kaboski (2001). In Mobius (2000), specialization in the product market changes endogenously over time. The economy starts at a low level of productivity, using a constant returns technology to produce specialized goods. When machines get more productive, the economy switches to an industrialized

[1] For some industries, for instance soap making, "flexible" machines were available well before the advent of modern numerically controlled machines.

economy. Because that technology exhibits increasing returns, the number of varieties depends on the size of the market. Initially the market is small and there are few varieties; subsequently the market is large enough to justify investment in machines for even very specialized products. Fordism can be seen as a transition between the artisan economy and the fully specialized industrialized economy. The skill premium rises as specialization falls, just as in this model.

In Mobius (2000), the rise of numerically controlled machines is due to the desire to provide specialized products using industrial techniques.[2] In other words, specialization is driving the nature of technological change, similar to the model of directed technical change in Acemoglu (1998). In this paper, the technological change is driving the change in specialization. This is consistent with the idea that the computer-aided technologies that have made flexible manufacturing possible arose for many other reasons other than the desire to increase specialization; rather, producers have taken advantage of specific scientific advantages. Historians such as Chandler (1977) have suggested that the rise in mass production was a result of a very specific change in the production technology: the availability of a rail network in the United States.

Caselli (1999) introduces a model where a technological revolution arises and can be either skill biased or de-skilling. In his model, skills increase the speed of learning. In this paper, skills make workers able to do more tasks, which is clearly closely related to the notion that skilled workers learn faster. In Caselli (1999), when a revolution brings new machines that are more learning-intensive, skilled workers relatively benefit, since they are best suited to the new machines. Kaboski (2001) also considers a model of the skill premium over the 20th century. Endogenous education choice and comparative advantage are the key forces.

2 Plant Size and the Wage Premium

At the beginning of the twentieth century, manufacturing was still largely based on craftspeople and artisans. The disparity in wages between high skilled and low skilled workers was dramatic. Figure 1 shows the time series

[2]Thesmar and Theonig (2000) use a similar model with increasing returns to scale to study the impact of globalization on the skill premium.

for the skill premium, measured as the return to one year of college, over the century. The data are from Goldin and Katz (2000).[3]

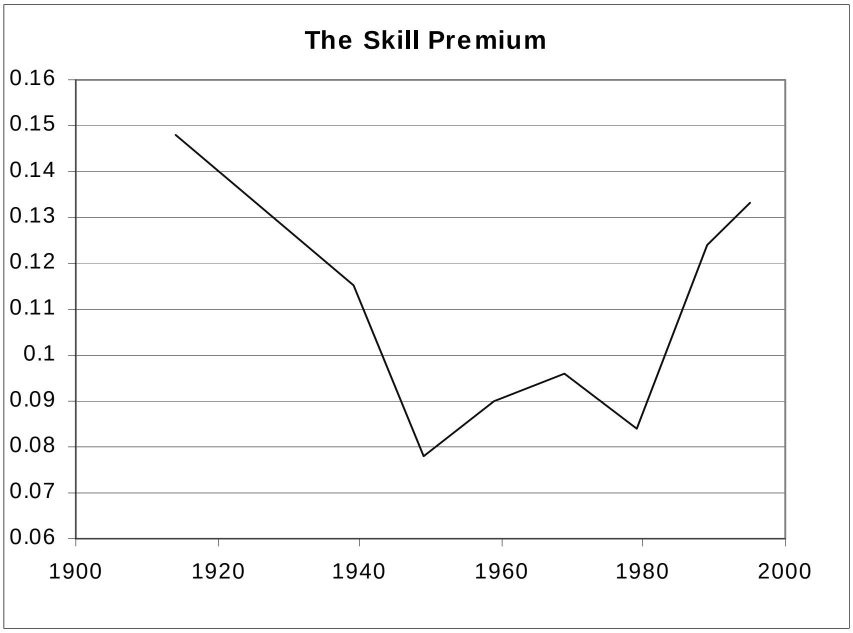

Figure 1: The Skill Premium

I choose to use the return to college because of the availability of a century-long series for it, but the primary features of the series are consistent with other measures of the return to skill and wage dispersion. For instance, the 90-10 or 80-20 wage ratio, looked at from the perspective of studies on various portions of the century, are similar: a fall in premium in the first half of the century, followed by an increase in the last quarter of the century. The return to high school, also reported in Goldin and Katz (2000) for the century, moves in a pattern very similar to Figure 1.

At the same time that the skill premium fell, plants became organized into larger entities. The reverse was true during the last part of the century. Figure 2 shows production workers per establishment from the Census of Manufactures[4].

[3]The premium is calculated for young men, by comparing the wages of those competing exactly 12 years of schooling to those completing exactly 16, and dividing by 4.

[4]The data prior to 1982 are taken from the 1982 Census. 1954 is missing the number of establishments, and therefore is eliminated.

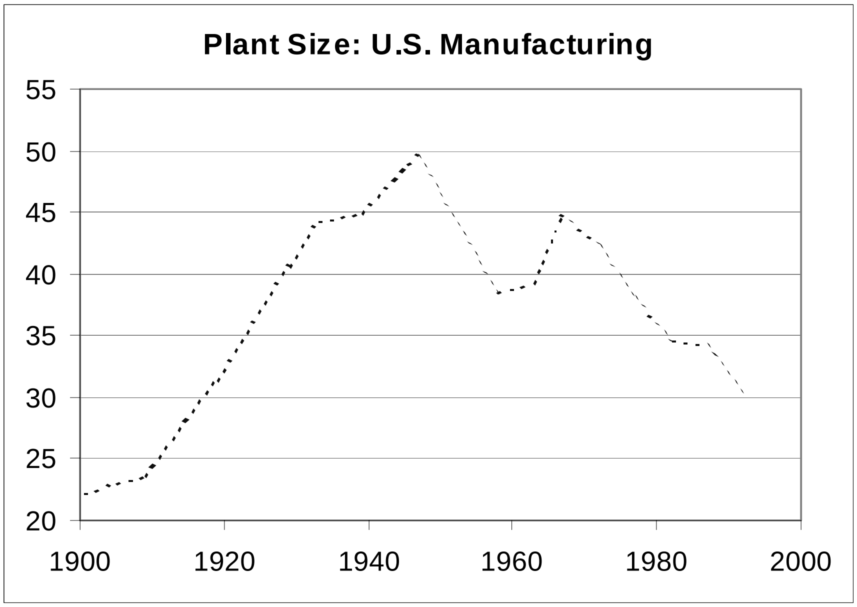

Figure 2: Plant Size

In the first half of the century, mass production and the rise of "Fordism" led to radical changes in the way production was organized. Craftspeople were replaced by assembly lines. The return to skill plummeted as jobs were routinized on the assembly line and workers did not need the same sorts of skills. In the last quarter of the twentieth century, the return to skill rose sharply. As the plant size data show, the organization of production also changed substantially over that period.

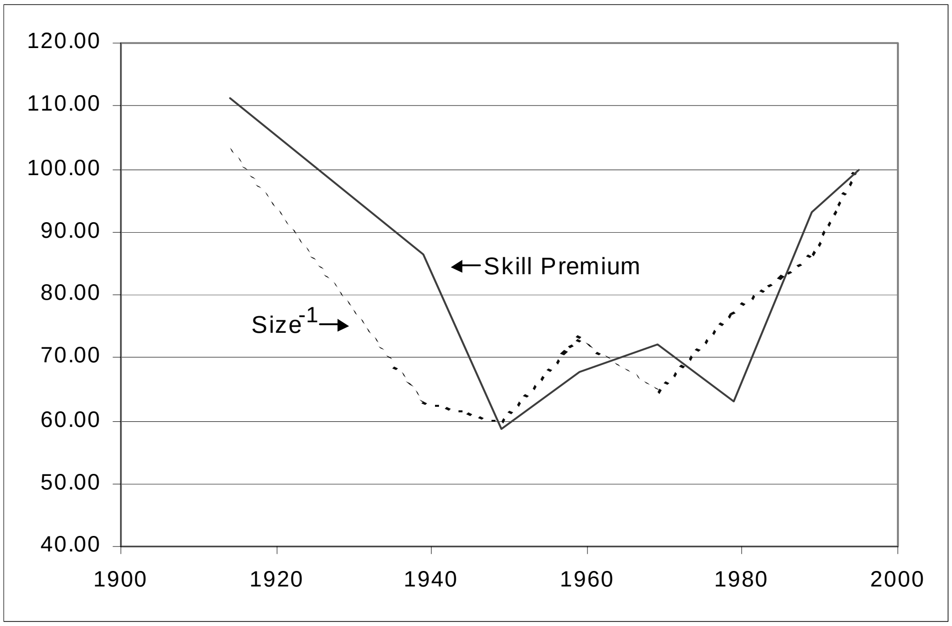

Figure 3: The Skill Premium and the Inverse of Plant Size

The recent decline in the size of establishments has been documented (see, for instance, Davis and Haltiwanger (1991)). Such a revolutionary change in the organization of production is interesting in its own right as an economic phenomenon to be documented and explained. That it is so closely related to changes in the wage premium makes it even more interesting. To see the relationship, consider Figure 3, which shows the skill premium and the inverse of plant size, as percentages of their 1995 values. The remainder of the paper is devoted to developing a model that has the feature that plant size and the skill premium are inversely related, and then to quantify the model to see to what extent it can help us understand the movement of the skill premium over the course of the century.

3 Modelling Input Flexibility

Information technology and numerically controlled machines have changed manufacturing (for a summary, see Comin (2000)). In this section, a model is introduced where the changes in plant size and wages come about due to changes in the "flexibility" of capital. The model captures the idea that high skill workers are more able to do a variety of tasks. One way to think of this is that skill brings flexibility. To induce changes in size over time, the model allows that the flexibility of capital might change. Flexibility of capital is modeled exactly as flexibility if modeled for workers: being flexible means being able to do a variety of tasks. When capital becomes more flexible, plants shrink and high skill workers benefit.

3.1 Plants

Each manufacturing plant does a variety of tasks with total mass 1. Each task is indexed by z. If the intensity of task z is equal to $x(z)$, then the output is

$$\left(\int_0^1 x(z)^{\frac{\sigma-1}{\sigma}} dz\right)^{\frac{\sigma}{\sigma-1}}$$

where $\sigma \in (0,1)$.

Each task is produced using two factors, capital and labor. For inputs k_z and l_z of the two factors, the intensity $x(z)$ is $x(z) = g(f(k_z, l_z))$, where f is a constant returns, constant elasticity of substitution production function with finite elasticity of substitution $\varepsilon \geq 0$, and g is a strictly concave function representing congestion of a fixed factor as in Lucas (1978). For simplicity, let $g(x) = x^\gamma$ for $\gamma \in (0,1)$. Since there is no gain in combining inputs of different skill levels within the same plant, and inputs will be optimally chosen symmetrically across tasks for a plant using a given skill level, there is no need to maintain the z subscripts on k and l. Instead, denote the inputs per task by k and l_j for a plant using workers of type j. Since the measure of tasks is one, gross output at a plant is $f(k, l_j)^\gamma$ and k and l denote both per-task intensities and per-plant totals.

Tasks require setup. This is the sense in which inputs have a level of flexibility: flexibility refers to being able to do a wide variety of tasks at low setup cost. A shipyard, for instance, might use a numerically controlled machine which can read a design from a computer file and cut the appropriately shaped piece of steel. A less flexible machine might be well suited to cutting a specific shape, but not as flexible in doing a variety of shapes (Kalpakjian (1995)). One way to interpret a plant at a point in time is as a batch: when low setup costs prevail, it is relatively inexpensive to make output in small batches: when setup costs are high, output must take place in large batches to be economical.

All inputs have setup costs. The setup cost per task is given by a_j for labor of skill level j and b for capital. Labor comes in many skill levels, indexed by a_j, where $j \in \{1, ..., N\}$ and $j' > j$ implies higher skill so $a_{j'} < a_j$. In a given time period, there is only one type of capital.

A natural measure of flexibility of capital is $1/b$: if $b = 0$, tasks have no setup costs, so capital can be spread across as many different tasks as desired with no loss, a sort of "infinite" flexibility. Notice that output is finite for a finite quantity of infinitely flexible capital, it just is not limited by the set of tasks. As b gets large, the set of tasks the capital undertakes must shrink if the capital is to be useful.

The model works equally well if one interprets b as a ratio of fixed to marginal costs. That is, a higher b amounts to a technology where fixed costs are relatively more important, as, say, fixed costs are higher but in turn lead to lower marginal cost for that input. To simplify the discussion, the marginal effect of capital is fixed here at one while b varies.

There is another sector in the economy with a constant returns production function and perfect substitutability between capital and labor, i.e., it produces non-manufactured output y_n with

$$y_n = K + L.$$

3.2 Consumers

The representative household has preferences for the manufactured good c_m and the non-manufactured good c_n described by

$$u(c_m, c_n) = (c_m)^\theta (c_n - \kappa)^{1-\theta},$$

where utility is zero when $c_n < \kappa$. Assume $\kappa > \max\{\bar{K}, 1\}$, so that both capital and labor will be used in the production of the non-manufactured good. This assumption is simply to guarantee that non-manufactured goods are not unrealistically 100 percent intensive in a single input.

The household has a fraction λ_j of its unit labor endowment in the form of skill level j and is endowed with $\bar{K}$ units of capital, and so faces the budget constraint

$$pc_m + c_n \leq \lambda \cdot w + r\bar{K}$$

for a vector of wages w and price of capital r. Manufacturing output has a price p. The non-manufactured good is the numeraire. Elastic labor can be easily added to the model; it is also straightforward (but cumbersome) to imbed this description of technology into a dynamic model of capital accumulation.

3.3 Equilibrium

There is free entry into each industry. Zero profits in the non-manufactured sector imply $r = 1$ and $w_1 = 1$. In manufacturing, since the mass of tasks is 1, and all are undertaken at the plant, the total setup cost is

$$rb + w_j a_j.$$

The setup cost acts as a fixed cost of $w_j a_j$ for labor and rb for capital. The manufacturing plant solves

$$\max_{k,l,j} pf(k, l_j)^\gamma - rb - w_j a_j - rK - w_j L_j = 0$$

where the equality comes from free entry driving profits to zero.

For manufacturing, denote $L^*_{m,j}(w)$ the labor demand for skill j and $K^*_{m,j}(w)$ the capital demand per plant with workers of type j. There is a mass M_j of manufacturing plants employing labor of type j. Total labor and capital demands are $L^*_{n,j}(w)$ and $K^*_n(w)$ for the representative firm in the non-manufactured sector. Denote $c^*_i(w)$ the final goods demanded by the household. Market clearing requires

$$L^*_{n,j}(w) + M_j(L^*_{m,j}(w) + a_j) = \lambda_j \ \forall j$$

$$K^*_n(w) + \sum_{j=1}^{N} M_j(K^*_{m,j}(w) + b) = \bar{K}$$

$$c^*_m(w, r) = \sum_{j=1}^{N} M_j f(K^*_{m,.j}(w), L^*_{m,.j}(w))^\gamma.$$

The non-manufactured sector clears by Walras' Law.

Next, the qualitative and quantitative predictions of the model for plant size and the skill premium are considered. In a later section concerning robustness, an alternative model specification is considered where the interest rate is fixed outside the economy (a "small open economy") and the non-traded sector is dispensed with. None of the following results are altered importantly. In that model, the specifications of the preferences and the non-manufactured sector are irrelevant; zero profit conditions in manufacturing are enough to determine the wages,[5] showing that the results are not hinging on the details of the specification of preferences and the non-manufactured good technology.

4 Capital Flexibility and The Skill Premium

4.1 Qualitative Results

The model has an unambiguous prediction about the connection between capital flexibility b and both plant size and the skill premium if the elasticity of substitution between capital and labor is small enough.

Proposition 1 *Suppose* $\gamma > \frac{\varepsilon-1}{\varepsilon}$. *The lower is b, the smaller are manufacturing plants, in terms of workers per establishment, and the larger is the skill premium,* $\log w_{j'} - \log w_j$, *for* $j' > j$.

The intuition for the condition on γ and ε is that the condition ensures that more capital at a plant raises the optimal number of employees at a given plant. To the extent that capital and labor are complements, capital increases the marginal product of labor and therefore increases the optimal labor choice. On the other hand, to the extent that there are decreasing returns at the plant level, increased capital makes the marginal product of labor lower, since it makes the bite of the decreasing returns more severe. The condition guarantees that the latter effect is outweighed by the former by assuming that the complementarity is large relative to the decreasing returns parameter.[6]

Notice that for $0 \leq \varepsilon \leq 1$, that is, for $f(k, l)$ ranging from Cobb-Douglas to Leontief (often considered the empirically relevant range), the condition holds immediately since $\gamma > 0 > \rho$. As the task level technology becomes perfectly substitutable between capital and labor, any decreasing returns will eventually lead to capital and labor being negatively associated.

[5] This is true so long as manufacturing uses all types of labor. The numerical exercise includes two types, so this is plausible.

[6] If the decreasing returns were just in labor, so that output was $f(k, g(l))$, the parameter restriction would be unnecessary.

Violation of the condition seems implausible, generally, since it would imply that plants with more employees employ less total capital, which is counterfactual. It is well known that plants with more workers not only employ more total capital, but in fact hire more capital per worker (see Hamermesh (1980)).

Under the regularity condition of proposition 1, an increase in b not only increases plant size, but it also decreases the skill premium. The intuition for the effect on plant size comes from the standard U-shaped cost curve. A rise in b makes the efficient plant size greater, because fixed costs per plant rise. This makes workers more specialized, that is, they perform fewer tasks. This allows workers with less skill to pay their setup cost on only a few tasks, and therefore makes the effective difference between them and the more highly skilled workers less severe. Their disadvantage at setup is mitigated by having fewer tasks to undertake at a large plant.

This result can be interpreted as saying that the model can qualitatively explain the experience of the twentieth century. Consider an economy where b varies. As b rises, plants get larger and the skill premium falls. This is an interpretation of the experience of the first half of the century. During the second half, b falls as capital becomes more flexible with the advent of numerically controlled machines, leading to smaller plants and a higher skill premium.

Next the model is parameterized to see to what extent it can quantitatively account for the movement of the skill premium.

4.2 Quantitative Analysis

4.2.1 Benchmark

The model is parameterized according to the following thought experiment. Suppose that there are two skill levels, $j \in \{1, 2\}$, corresponding to low skill and high skill, with costs a_2 and a_1 There is a sequence of time periods, each with a specific b_t and share λ_t of skilled workers, but with a constant flexibility of unskilled labor a_l.

Normalize a_2 to zero. The fraction of workers with skills is exogenous but potentially changing over time (λ_t). Since the skill premium is calculated as the return to college, the fraction skilled is the fraction of college educated workers.[7] The flexibility parameter for capital, b, varies over time exogenously. The interpretation is that the ratio of fixed to marginal costs for capital changes over the century. Fixed costs are relatively unimportant for the craft industry. The rise of mass production stems from a technology where a fixed cost is followed by the low marginal cost of the assembly line. Flexible manufacturing lowers the importance of the fixed cost as huge factories are no longer required to take advantage of mechanization.

As a benchmark assume $f(k, l)$ is Cobb-Douglas, $l^\alpha k^{1-\alpha}$. The parameter α is taken to be .66 to reflect the ratio of labor's share to capital's share of output. Again as a benchmark, let $\gamma = .9$, which implies that the share of income accounted for by fixed factors is ten percent. McGrattan and Prescott (2000) report that "intangible capital," which can be interpreted as the sort of managerial input that is congested and leads to decreasing returns at the plant level, has a five percent share of output. If structures are thought of as a fixed factor, some of their 15 percent share should be included. Gort et al. (1999) use a seven percent "profit rate," which corresponds to $\gamma = .93$ in the model. In the next section we consider a variety of values for γ.

What is left to parameterize is the sequence of b_t and the low skill flexibility a_l. Those parameters are chosen so that the model replicates the average manufacturing plant size in each period, and so that the skill premium in the final period (1995) is matched exactly.[8] There are T+1 equations necessary to uncover the T+1 unknowns, namely the sequence of b_t and the constant a_l. The results then imply, through the model, a skill premium series that can be compared to the data.

If the optimal size at time t of a plant with high skill workers is $L_{2,t}$ and with low skill workers is $L_{1,t}$, the average size is[9]

$$\bar{L}_t = \left(\frac{\lambda_t}{L_{2,t}} + \frac{1 - \lambda_t}{L_{1,t}} \right)^{-1}.$$

There are T such equations to match the average size in each period, plus an equation for the skill premium in 1995.

[7] The results do not hinge crucially on this fraction. Alternatives are considered in the next section.

[8] It is straightforward to match the average skill premium over the century. The results from that parameterization are very similar, since the model's predicted skill premium in that case is quite close to the premium in 1995.

[9] Since the consumer has Cobb-Douglas preferences, the total amount of labor devoted to manufacturing is constant. The argument is contained in the proof of proposition 1.

The model's predicted skill premium for the century is reported in Figure 4.

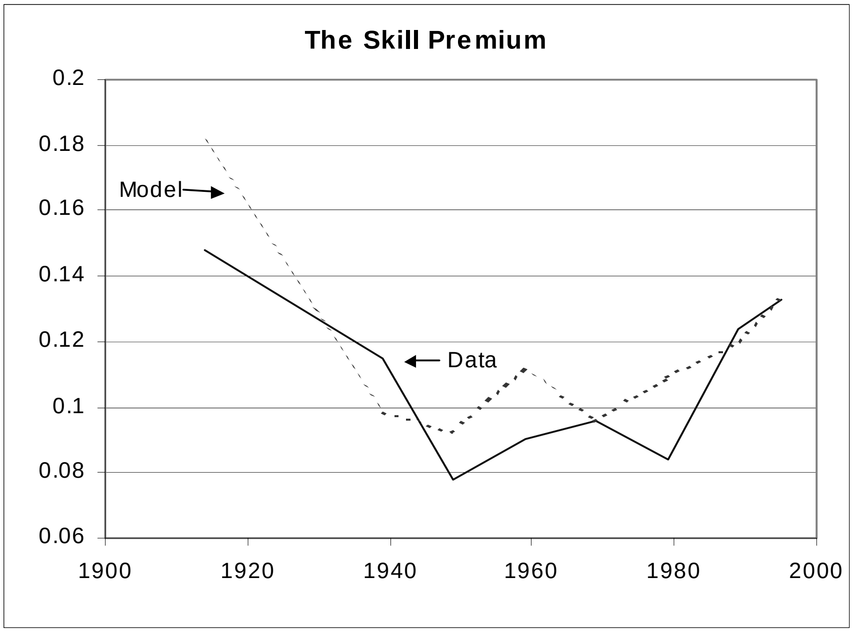

Figure 4: Cobb-Douglas Model

The R^2 of this model is .66.

The motive in using capital flexibility as a driving force for change is evidence that numerically controlled machines bring increased flexibility (Comin (2000), Milgrom and Roberts (1990)). The model generates a measure of the magnitude of the change in flexibility of capital. From the peak in plant size (around 1970) until the last data point (in 1995), the per-task setup cost for capital falls by slightly more than a third in the model. The calibration implies that the ratio of setup costs for unskilled labor to the unskilled labor wage bill is modest, about 10 percent throughout the century. The next section considers some alternative parameters to check the robustness of the experiment.

4.2.2 Robustness

Various changes to the parameters above were considered. As a variant from the assumed Cobb-Douglas form for $f(k, l)$, consider instead the extreme case where $f(k, l)$ is Leontief, the opposite end of the empirically relevant range.

The results were very similar, in terms of R^2 for the model's predicted skill premium relative to the data; the model is a bit more accurate at the start of the century, but less in the middle, as shown in Figure 5.

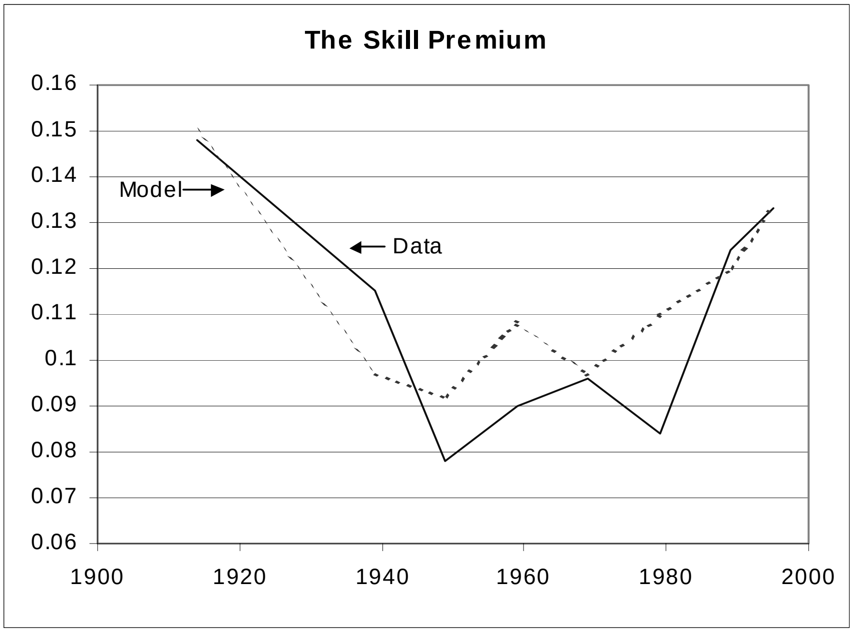

Figure 5: Leontief Case

As a century-long series for the college premium is readily available, λ_t has been taken from data on college education; one might think that is peculiar since it is such a low number (around 3%) at the early part of the century, or because of a definition of skills other than those that come from college education. To verify that supply side changes are not at the heart of the model's prediction, another approach to λ is considered. Imagine defining skills to be the top 20% of the population, so $\lambda = .20$ constantly. Now the college premium is only a proxy for the skill premium, and the exercise with constant λ is not consistent with using the college premium. It is useful, though, since studies show that other measures such as 80/20 ratios move in a similar manner to the college premium for various periods of the century.

In addition, since a precise value of γ is not available, the computation was rerun with γ ranging from .8 (using all of the share of intangible capital and structures) to .95 (in excess of the Gort, et al. (1999) figure, adding nothing for structures). The following table displays the results, in terms of the model's R^2, for both of the production functions f.

	Cobb-Douglas			Leontief		
		λ:College	λ:20%		λ:College	λ:20%
R^2 :	γ =.80	.64	.60	γ =.80	.66	.60
	γ =.90	.66	.60	γ =.90	.64	.59
	γ =.95	.61	.57	γ =.95	.50	.56

The results are not altered substantially; the model explains an important fraction of the variation, with an R^2 between .56 and .66 in all but one of the 12 cases, despite using extreme parameter values. The supply of skills plays only a small role in the model: when the supply of skills is low, the fraction of small plants (the ones with highly skilled workers) falls, and so capital must become more flexible to maintain the same average plant size. Comparing the beginning of the century to the end, the plant size is similar, so the model implies a similar b and therefore a similar skill premium if λ is the same. The low λ at the turn of the century means that capital must be more flexible to generate the same plant size prediction, and therefore the predicted skill premium is higher at the start of the century when λ varies. Using the return to high school and taking λ to be the fraction with a high school education once again delivers very similar results, in terms of variation of the skill premium explained.

As another check of robustness, the skill premium was computed for the "small economy" case where the interest rate was fixed and the specification of the non-manufactured sector and consumer preferences is not important. The results were almost the same as the ones reported above, where the general equilibrium is computed. The results do not depend critically on the specification of the model outside of the manufactured goods technology.

The key channel in the model is that changes in the optimal plant size affect specialization and in turn affect wages. Because of evidence that machines became more flexible at the end of the century, the driving force of change has been taken to be the flexibility of capital. Another natural force in determining plant size is returns to scale (γ), which has been held constant in this exercise. Another experiment would be to hold constant the fixed costs from flexibility of the inputs (a and b), and vary the returns to scale parameter γ to match the varying average plant size over the century.

In order to see how successful this might be, let $\gamma_{1995} = .85$, in the middle of the relevant range, and choose the fixed costs of high skill and low skill plants (equivalent to using $a_1 + b$ and b from the model of flexibility) to match precisely the average size of plants and skill premium in 1995. Then, holding fixed these a_1 and b, choose γ_t for all other time periods to match the average size of plants in each period. For 1995, a relatively small value of γ (.85) is chosen from the reasonable range since the computed γ_t is the lowest when the skill premium is highest. The middle of the century returns values for γ closer to one. The simulation produces similar results to the earlier experiment, in terms of having an R^2 near 0.6. The important feature of the model – and the message of the paper – is that specialization increases with plant size and decreases the skill premium.

5 Industry Evidence

5.1 Changes in Size and Skill

The relationship between specialization and the skill premium can also be studied by looking at more narrowly defined manufacturing industries. To interpret changes in the cross section of industries, consider a model with many manufacturing industries. Output in a given industry is

$$y_m^i = \sum_{j=1}^{N} M_j^i f(K_{m,.j}^{*i}(w), L_{m,.j}^{*i}(w))^{\gamma}.$$

The industries are of total mass one; output is aggregated to get manufacturing output:

$$y_m = \left(\int_0^1 (y_m^i)^{\alpha} dy_m^i \right)^{\frac{1}{\alpha}}$$

where $\alpha < 1$.

A plant engaged in producing manufacturing output from the output of the various industries solves

$$\max_{y_m^i} \left(\int_0^1 (y_m^i)^{\alpha} dy_m^i \right)^{\frac{1}{\alpha}} - \int_0^1 p_i y_m^i dy_m^i.$$

Industries differ by the capital cost parameter b_i. We have the following similar comparative static to the prior section:

Proposition 2 *Suppose* $\gamma > \frac{\varepsilon-1}{\varepsilon}$. *If* b_i *is higher, then industry* i *has larger plants for a given skill level* j *and pays lower wages in equilibrium.*

Goldin and Katz (1998) report that industries that underwent organizational change in the first part of the century leading to batch methods of production hired more skilled workers than did industries that moved to traditional assembly line methods. They point out (p. 698) that the "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" while the "transition, from the artisanal shop to the factory, appears to have involved an opposite force."

It is not surprising that the skill premium was falling, on the whole, during the first half of the century since the plant size data suggest that the rise of mass production was leading to increased specialization (see also Chandler (1977)). However, for those industries that did move to batch processes during that period (the industry with falling b_i, allowing for flexible batch production), the result was the hiring of a more skilled workforce. In addition to the force outlined in the proposition, skilled workers were becoming relatively cheaper.

In the latter part of the century, on the other hand, industries adopting batch processing technologies with flexible capital were the dominant force, as seen in the downward trend in average manufacturing plant size. Using wages as a proxy for skill, the panel of industry aggregate data for manufacturing from 1977-1994 allows one to see how industry wages change as the size of plants changes.[10]

Estimating the fixed effects regression

$$w_t^i = \alpha^i + \beta l_t^i + \varepsilon_t^i \tag{1}$$

where w_t^i is defined as compensation of production workers divided by hours of production workers and l_t^i is production workers per establishment, gives a significant and *negative* coefficient for β.[11] The interpretation is that, conditional on the size of plants in an industry on average over time, increases in size are negatively associated with the wages paid. The relationship in

[10] These data, taken from aggregates in the County Business Patterns data set, are freely available as a panel, unlike the plant level data. The panel includes data on average size and average wages for each industry.

[11] It is also more than twice as large, in absolute value, as the one computed without the fixed effect for industry.

(1) is robust to controlling for total employment in the industry, so the relationship is not simply caused by increases in total employment leading the industry to hire less capable workers.

One counterfactual feature of the model is that in the cross section of manufacturing plants arising in equilibrium, larger plants hire lower skilled workers and therefore pay lower wages. A long tradition of empirical work (for instance Davis and Haltiwanger (1991) and Brown and Medoff (1989)) finds the reverse to be the case. In fact this correlation can be illustrated in the data used in (1), either by a simple regression on all of the data or in cross-sectional regression run year-by-year. The robustness of the size-wage premium makes the negative coefficient in (1) even more striking.

Many theories have been proposed to explain this size-wage premium (see Brown and Medoff (1989) for a discussion). This theory complements those theories, in the sense that differences across industries, which follow the usual positive size-wage relationship, are best explained by the existing theories. This is not surprising, since variation in size across industries is related to a wide variety of features, such as the breadth of tasks undertaken at each plant, and is therefore not likely to be primarily driven by differences in capital flexibility. The model introduced here is useful, however, in understanding how changes in size influence wages, conditioning on industry as in (1).

5.2 Other Evidence

Dunne, et al. (2000) find that investment in computers is an important determinant of wage dispersion across plants in the period from 1975. Since the sort of flexible machines that allow for batch methods are closely connected to computers, these results further point to the relationship between the organization of production and the distribution of wages.

Suppose that industries which are intensive in flexible manufacturing have achieved increased unmeasured quality of capital. Then total factor productivity growth is a proxy for such industries. Consider the relationship

$$l_t^i = \alpha^i + \beta \Delta TFP_t^i + \varepsilon_t^i$$

where ΔTFP_t^i is the rate of total factor productivity growth in industry i at time t. The coefficient β is negative and significant, indicating that industries that adopted these technologies downsized, as the model predicts would happen as a result of more flexible capital. Moreover, an increased rate of technological progress has been associated with higher wages: the relationship

$$w_t^i = \alpha^i + \beta \Delta TFP_t^i + \varepsilon_t^i$$

yields a positive and significant coefficient for β. So the idea that flexible machinery has led to smaller plants and higher wages is in accord with at least this basic analysis.

Ingram and Neumann (2000) suggest that certain skills, particularly mathematical skills, have seen a particularly high return over the recent U.S. experience. To the extent that numerically controlled machines are said to put more focus on mathematical skills, their finding is consistent with the idea that flexible capital has had an important effect on the skill premium.

6 Summary

Explanations of the recent rise in the skill premium have centered on the role of skill-biased technological change. The experience of the first half of the century shows that the nature of technological change has an important impact on whether it relatively favors the skilled or unskilled. The rise of mass production made fixed costs high relative to marginal costs. Later, fixed costs became less important.

Data from plant size can be used to understand the degree of specialization of labor over the century. The model assumes that specialization relatively favors the unskilled; routinized jobs, very narrow in scope, can be accomplished efficiently by workers with less skill. The model is parameterized to match the facts on the organization of production throughout the century, as well as the skill premium at the end of the century. The results show that using evidence from the organization of production can aid in the understanding of the skill premium.

The model provides an explanation for why technological change seems to be skill-biased at times and de-skilling at others. The key is whether or not the technological change made workers more specialized, as with the rise of "Fordist" mass production, or less specialized, as with the recent adoption of numerically controlled machines. Using plant size as a measure of specialization, times of high plant size seem to correlate with times of relatively low returns to skill. Moreover, studies of industries that adopted technologies near the beginning of the century which had the batch-process flavor of the technologies which became more prevalent at the end of the century show that technologies which make workers less specialized have been skill biased even at times when the aggregate trend is the reverse.

There are three ingredients to the explanation of the connection between plant size and the skill premium. First, the ability of capital to do a wide variety of tasks has changed over time. When capital can do a wider variety of tasks, it can be divided into more plants to avoid plant-level decreasing returns.

Second, changes that increase capital per plant also increase labor per plant. In order to show that flexible capital leads to smaller plants and a higher skill premium, capital must be sufficiently complementary to labor, relative to the decreasing returns at the plant level. This restriction is natural, in the sense that if it is violated, plants that are large in terms of employment are the smallest in terms of capital, which is counterfactual. The important feature is that jobs are more specialized as plants get larger.

The final ingredient is that, for labor, skills make a worker relatively more productive at doing a variety of tasks. Low skilled workers are particularly effective when they are given a small scope of tasks to perform, and therefore, are relatively more productive when capital is inflexible and optimally allocated into fewer, larger plants.

Sokoloff (1986) stresses that changes in the organization of production in the first half of the century were not necessarily linked to physical capital. Although the results take capital flexibility as the driving force of change, it is not essential. The changing nature of capital is taken as the force of change because it has been suggested as an important one for the latter part of the century. The basic message, that changes in the first half of the century increasing plant size led to more specialized jobs, and that this lowers the skill premium, does not depend on this particular formulation.

One might argue that manufacturing plant size is only a quite noisy measure of the degree of specialization in the economy. To that extent, it is perhaps even more interesting that the model is able to explain such a fraction of the movement in the skill premium. The model holds fixed many factors that are important over the century. The scope of plants is fixed. The supply of skills is exogenous. In view of the limitations of the model, the extent to which it succeeds in explaining the broad patterns of the skill premium over the century is all the more startling, and suggest future analysis of the role of the organization of production in determining the skill premium. This connection provides a foundation for understanding the causes of skill bias in technological change.

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Appendix: Proofs

Proposition 1

Denote the task level production function by

$$f(k,l) = (\alpha k^{\rho} + (1-\alpha) l^{\rho})^{\frac{1}{\rho}}$$

with $\alpha \in (0,1)$. The profit function for a plant hiring a given type of labor is

$$p(\alpha k^{\rho} + (1-\alpha) l^{\rho})^{\frac{\gamma}{\rho}} - wl - rk - wa - rb \tag{2}$$

Take two skill levels a_h and a_l with $a_h < a_l$. To show that the skill premium for type h is decreasing in b, first consider the case of $\gamma = \frac{\varepsilon-1}{\varepsilon}$, i.e., $\rho = \gamma$. In that case, the profit function for a plant hiring a given type of laboris separable in capital, so b has no effect on the wage.

On the other hand, for $\rho \to -\infty$, the Cobb-Douglas case, it is easy to verify by direct calculation that the log wage premium is

$$s = \log w_h - \log w_l = \eta \left(\log(a_l + b) - \log(a_h + b)\right)$$

for some positive constant η, so s is clearly decreasing in b for small enough ρ.

The range $\gamma > \frac{\varepsilon-1}{\varepsilon}$ corresponds to $-\infty < \rho < \gamma$. Since $\frac{ds}{db} = 0$ for $\rho = \gamma$ and $\frac{ds}{db} < 0$ for $\rho \to -\infty$, then if $\frac{ds}{db}$ is positive for some ρ in the range, the implicit function theorem implies that there is some ρ in the range where $\frac{ds}{db} = 0$. We now show that this implies a contradiction, i.e., that $\frac{ds}{db} = 0$ is impossible in equilibrium.

The zero profit conditions are

$$p(\alpha k_j^{\rho} + (1-\alpha) l_j^{\rho})^{\frac{\gamma}{\rho}} - w_j l_j - r k_j - w_j a_j - b = 0$$

where k_j and l_j are the input choices per task of a firm hiring labor of type j. Differentiating with respect to b and applying the envelope theorem,

$$-l_j \frac{dw_j}{db} = 1 \tag{3}$$

so

$$-l_j w \frac{d \log w_j}{db} = 1$$

and since $\frac{ds}{db} = 0$

$$l_h w_h = l_l w_l$$

which implies $\frac{d(\log l_l - \log l_h)}{db} = 0$.

The first order conditions for capital and labor are

$$\begin{aligned} p(1-\alpha)\gamma(\alpha k_j^\rho + (1-\alpha)l_j^\rho)^{\frac{\gamma}{\rho}-1} l_j^{\rho-1} &= w_j \\ p\alpha\gamma(\alpha k_j^\rho + (1-\alpha)l_j^\rho)^{\frac{\gamma}{\rho}-1} k_j^{\rho-1} &= 1 \end{aligned} \tag{4}$$

so

$$(1-\alpha)\gamma\left(\alpha\left(\frac{w_j\alpha}{r(1-\alpha)}\right)^{\frac{\rho}{1-\rho}} + (1-\alpha)\right)^{\frac{\gamma}{\rho}-1} l_j^{\gamma-1} = w_j$$

so the log wage differential is

$$s = \log((1-\alpha)\gamma) + (1-\gamma)(\log l_l - \log l_h) + (\frac{\gamma-\rho}{\rho})(\log x_h - \log x_l)$$

where $x_j = \left(\alpha\left(\frac{w_j\alpha}{r(1-\alpha)}\right)^{\frac{\rho}{1-\rho}} + (1-\alpha)\right)$. If $\frac{ds}{db} = 0$, $\frac{dx}{db}$ must be zero since $\frac{d(\log l_h - \log l_l)}{db} = 0$. But this implies $w_h = w_l$, which is impossible for $a_l > a_h$ (both could not make zero profits). Therefore, $\frac{ds}{db} < 0$ for all $\rho \in (-\infty, \gamma)$.

To show that size is increasing in b, first I show that size is increasing in b for plants with each skill level of worker j. From (3), $\frac{dw_j}{db} < 0$. From (4), it is easy to verify that l_j is decreasing in the wage, so l_j is increasing in b, i.e., workers per plant of type j are rising in b.

Since workers per plant for the plants that hire type j are $\frac{\lambda_j}{M_j}$, the number of plants must be decreasing in b for all j. Since, given the Cobb-Douglas preferences, total spending on each good is constant, the total of capital and labor employed in the non-manufactured good is independent of b. Since the capital-labor ratio in manufacturing is constant, the number of employees in manufacturing is a constant L_m, and average size is

$$\frac{L_m}{\sum_j M_j}.$$

Since the number of plants is decreasing in b for all j, the sum must be as well, so average size is increasing in b.

Proposition 2

The previous proposition established that size l_j is increasing in b for plants with a given skill level of worker j. The marginal benefit of employing workers with higher j is

$$-l_j \frac{dw_j}{dj} - w_j \frac{da_j}{aj}. \tag{5}$$

Since $\frac{dw_j}{dj} \geq 0$ and l_j is increasing in b, (5) is decreasing in b. Therefore the higher is b, the less is the benefit to employing additional skill, and therefore industries with higher b will employ lower skilled workers. The matching of workers to firms will follow a pattern where the highest skilled workers are matched to the industries with the lowest b, and so on.