More Machines or Better Machines?

by James Bessen

(Boston University School of Law, Research on Innovation)

working paper

Version: 11/08

Abstract: This paper assesses how much of the rapid growth in labor productivity in nineteenth century cotton weaving arose from capital-labor substitution and how much from technical change. By using an engineering production function and detailed information on major inventions, I find that labor-saving technical change accounts for almost all of the growth. However, much of the labor-saving bias arose not from inventions, but from acquisition of new knowledge and skills by weavers. Moreover, this was endogenous, influenced by wages and prices. This provides a technology-based explanation for the persistent association between economic growth and capital deepening.

Keywords: technical change, productivity growth, technical bias, innovation

JEL codes: O33, O47, N61

Contact: jbessen@bu.edu

A weaver in the U.S. in 1902 produced over 25 times as many yards of cloth in an hour of weaving as did a weaver a century earlier producing a comparable cloth. The weaver in 1902, however, achieved that output using seven or eight power-driven looms while the weaver of 1802 used a single handloom. Similar patterns of productivity growth accompanied by capital deepening are seen in many other technologies.

How much of this growth in labor productivity came from "more machines" and how much came from "better machines"?[1] That is, to what extent was it driven by simple capital accumulation that pushed production to more capital intensive techniques on the production possibilities frontier and to what extent was it driven, instead, by a process of technical change that introduced new techniques that were both more productive and more capital intensive? In the "more machines" story, rising wages (relative to capital costs) drive capital deepening. In the "better machines" story, biased technical change plays this role. This paper attempts to assess how much of the growth in labor productivity in nineteenth century weaving arose from factor substitution and how much from biased technical change and what caused such bias. I do so by looking in detail at the inventions, the capital deepening and the realized productivity improvements.

The question of "more or better machines" is important for understanding nineteenth century economic growth. At least since Hicks (1932), biased technical change has been seen as a feature of economic development. For example, analyzing macroeconomic data, Abramovitz and David (1973, 2001) argue that a labor-saving/capital-using bias accounts for the substantial capital deepening that occurred in the nineteenth century United States. And this affected the character of economic development.

The question of "more" vs. "better" machines is also relevant to modern economic development policy. For example, scholars have recently debated the relative roles of capital accumulation and technical change in East Asia's rapid growth (see Kim and Lau 1994, Nelson and Pack 1999, Rodrik 1997, and Young 1995). This issue affects the extent to which development policy needs to focus on macroeconomic incentives to encourage saving or to focus on, instead, the institutions that foster technological change.

This paper explores technical change and factor substitution by looking in detail at the major inventions adopted in nineteenth century U.S. cotton weaving and I relate these to the performance of

---

[1] This language comes from the literature on the differences in capital intensity and labor "scarcity" between early America and the England, including Rothbarth (1946), Habakkuk (1962), Temin (1966b), Fogel (1967) and Clarke and Summers (1980).

cloth production over time. Cotton weaving is not just any technology. Textiles were a leading sector in the Industrial Revolution in the United States and Britain. Clark (2007, p. 233) attributes over half of the productivity gain achieved between 1760 and 1860 in England to gains in textile production, with most of this gain coming from cotton.[2] In Japan, cotton textiles became the first industry to dominate export markets. Japan went from being a net importer to the world's largest exporter in a matter of decades (Toyota began as a loom manufacturer). Cotton textiles have also been an important industry in China's recent economic growth. So cotton has been an historically important sector.

But the big advantage of studying cotton textile technology is that it is a simple mechanical technology that has been extensively researched. Because detailed information is available, I can measure the rate, the bias, and the sources of technical change. First, I build an engineering model of cloth production and show that the technology imposes constraints on the nature of technical change and factor substitution. Three types of technological improvements in productivity were possible: one that is purely labor-augmenting, one that is purely capital-augmenting, and one that enhances labor and capital efficiency in fixed proportions. Technology also limits the elasticity of substitution between labor and capital. I then look at the major inventions that were widely applied to weaving during the nineteenth century and seen as important by contemporaries. Using data from a variety of sources including trade publications, patent specifications, weaving manuals and measurements taken on working museum models, I estimate the increases in labor and capital efficiency brought by each invention. Using data on realized performance at large mills, I validate these estimates and identify other sources of productivity growth.

My model is an example of what Chenery (1949) called an “engineering production function.” Chenery recognized that detailed engineering models could help disentangle factor substitution from technical change. But only a limited number of researchers have attempted to build such engineering models (see Wibe 1984 for a review) and only a few of these papers have looked at technical change (for example, Smith 1957, and Pearl and Enos 1975). A literature in agricultural economics has also built engineering-like models and has used these to look for empirical evidence of induced innovation (see Ruttan 1997 for a review). This paper not only separates the effects of factor substitution from technical change, but I also use the engineering model to investigate the contributions that major inventions made to technical change over a century and also the contribution of on-the-job learning.

Beginning with Brown and De Cani (1963), David and van de Klundert (1965), and Ferguson

---

[2] Harley (1999), using a revision of McCloskey’s estimates (1981), attributes 36% of the UK productivity growth between 1780 and 1860 to textiles.

(1965), econometric studies have estimated technical bias for aggregate production functions, generally rejecting the null hypothesis of Hicks neutrality.[3] My analysis confirms a finding of technical bias at the micro level, but it also reveals important details about the nature and origins of this bias.

Since Rothbarth (1946) and Habakkuk (1962), researchers have proposed that the technical bias might respond endogenously to economic factors, leading, for example, to the adoption of more capital-intensive techniques in the U.S. than in England. Several theoreticians formalized the intuition about factor prices affecting the bias of innovation by introducing an "innovation possibilities frontier" (Ahmad 1966, David 1975, Fellner 1961, Kennedy 1964, Samuelson 1965). Nordhaus (1973) criticized much of this literature for failing to provide much of an explanation, since the innovation possibilities frontier itself was seen as an exogenous construct. Recently, Acemoglu (2003, 2007) presented an endogenous growth model that, under some assumptions, leads to labor-augmenting technical change. Jones (2005) proposes a search model for inventions that, under some assumptions, leads to a Cobb-Douglas production function (so that all technical change is equivalent to labor-augmenting change). However, aside from studies in agricultural economics (Ruttan 1997), little direct empirical evidence has been found to explain what appears to be a persistent and important technical bias.

My engineering analysis finds a source for the labor-saving bias, but one that differs from most of the theoretical literature. The literature on induced innovation tends to assume that the bias in technical change arises from the choice of *inventions* that firms adopt. But I find that the inventions adopted during the nineteenth century only exhibit a modest labor saving bias when evaluated at their initial adoption. Instead, much of the labor-saving bias appears to arise from the way the inventions were implemented over time, especially with regard to on-the-job learning. Moreover, the evidence suggests that firms' investment in learning responds endogenously to factor prices in a rather straightforward way.

This bottom-up approach reveals a richer picture of technical change and growth than can be gleaned from aggregate statistics alone. My findings are limited to the technology of cotton weaving, however, other technologies of mechanization—technologies responsible for much of nineteenth century economic growth—share similar constraints and therefore these technologies might share a similar endogenous response to economic conditions.

---

[3] Empirical studies that formally test and reject the hypothesis of Hicks neutrality include Antras (2004), Berndt and Khaled (1979), Binswanger (1974), Brown and De Cani (1963), David and van de Klundert (1965), Ferguson (1965), Jorgenson and Fraumeni (1981), Kalt (1978), Klump et al. (2007). May and Denny (1979), Moroney and Trapani (1981), Panik (1976), Sato (1970), Wilkinson (1968), Wills (1979) and Yuhn (1991). Berndt and Wood (1982) could not discriminate between different technical biases. Toevs (1980) could not reject the Hicks neutral hypothesis against a restricted alternative. Berndt et al. (1993) reject Harrod neutrality, but could not reject Hicks neutral technical change.

The next section provides some background and develops the engineering model. Section 2 explores the major nineteenth century inventions in weaving and their effect on capital and labor efficiency. Section 3 explores factors that might account for the observed bias in technical change that does not appear to be accounted for by the major inventions. Section 4 does a growth accounting and Section 5 concludes.

Weaving Technology and Technical Change

Biased Technical Change

Hicks (1932, p. 121) classified technical change depending on whether the initial effect was "to increase, leave unchanged, or diminish the ratio of the marginal product of capital to that of labour." He identified labor-saving (capital saving) changes as those that increased (decreased) the ratio of the marginal products. At constant factor prices, profit maximization implies that the ratio of factor prices equals the ratio of marginal products. To maintain this equality, firms will change factor proportions in response to Hicks-biased technical change. Specifically, with constant factor prices, a labor-saving technical change induces an increase in the capital-labor ratio while a capital-saving changes induces a decrease. This means generally that both changes in factor prices and biased technical change can alter factor proportions as well as labor productivity.

Because the distinction between factor substitution and technical change is subtle, a detailed look at technology might help disentangle this difference. Factor substitution concerns a change from the currently used technique to another already-known technique, usually in response to changing factor prices. Technical change, on the other hand, involves a change to a new, previously unknown technique arising from the development and application of new technical knowledge, often, but not always, an invention. The problem is, economists rarely have detailed information about the state of technical knowledge; they simply lack information about which techniques are known when. If all they observe is aggregate data, they cannot usually distinguish between these two changes unambiguously. Indeed, as Diamond et al. (1978) show formally, neither the production function nor the path of technical change are identified when empirical researchers only have aggregate data on inputs, outputs and prices over time, without some additional structure. Since most of the research on these questions has been based on aggregate statistics, economists often impose *a priori* assumptions about the shape of the production function and/or the rate and bias of technical change.[4]

---

[4] Unfortunately, different branches of economics commonly make different, mutually inconsistent assumptions.

The engineering production function approach avoids this difficulty. As we see next, the engineering production function determines the extent of capital-labor substitution and it determines the technical biases produced by different kinds of inventions.

Mechanization

Weaving is one of many technologies that were mechanized during the early nineteenth century. Mechanization involves the application of machines driven by inanimate power to tasks previously performed by human or animal power. Typically, mechanization brings three main advantages:

1. More machines can be used per worker. Weavers can tend more than one loom and spinners can handle hundreds of spindles.
2. Machines can be run faster.
3. Well-regulated machines can sometimes produce higher quality goods, for example, finer yarns or more even cloth.

I focus on the first two advantages because they are easier to measure. I control for quality by looking at weaving on relatively a relatively standard set of coarse cloths (about 50 threads to the inch of weft, using plain weaves, typically sheeting, shirting or print cloths, 36 inches wide).

Weaving is performed by interlacing two sets of threads, the warp and the weft, at right angles to each other. The warp consists of long, closely spaced threads that are stretched between two beams, the warp beam, for the bare warp threads, and the cloth beam, for the woven cloth. For the looms I study, the warp threads might be two or three hundred yards long with 1,800 or so threads across. Each warp thread passes through a small opening in a “heddle” that is used to raise or lower the thread. The loom alternately raises and lowers different sets of warp threads creating an opening called a “shed.” A shuttle holding a bobbin of weft yarn (also called “filling”) is propelled through the shed across the warp, leaving a new weft thread behind. This motion is called “picking” and the speed of the machine is frequently expressed in picks per minute. The weft thread left by the shuttle is pushed against the previously woven cloth by a comb-like “reed” (the process is called “battening”), adding it to the cloth. The entire process is repeated over and over again with different sets of warp threads raised and lowered for each pick according to the specific weave pattern.

The tasks of shedding, picking, battening, letting off warp from the warp beam and taking up cloth on the cloth beam were all performed manually (with some mechanical assistance) by handloom

---

Productivity researchers often assume Hicks neutrality while neoclassical growth theorists assume purely labor augmenting technical change. As noted above, other researchers assume that the technical bias is endogenous, possibly changing over time.

weavers and these tasks were all automated on the first power looms. This automation generally allowed a skilled weaver to tend two power looms at a time instead of one handloom. Also, these power looms generally ran at faster pick rates than those that handloom weavers realized.

While mechanization reduced the labor required to produce a given output, it did not eliminate the need for labor. There are two reasons for this. First, some tasks were too difficult to automate, at least at first. For example, when the bobbin ran out of weft yarn, the loom had to be stopped and the empty shuttle replaced by one with a full bobbin. This task was performed manually until the appearance of the Northrup loom at the end of the nineteenth century. Second, the machines were hardly perfect. In textiles, for example, effective operation of the machines was sensitive to variation in humidity and temperature and of the quality of raw materials; also, the machines themselves were subject to breakdowns and sometimes depended on sensitive adjustments. Yarn would break and shuttles would fly out of the looms or get stuck in the emerging cloth.[5] These errors took time to fix.

Generally, the time to perform non-mechanized tasks and the time to fix errors determined the efficiency of the machines for a given speed of operation. Although a loom might run at a speed capable of producing, say, four yards of cloth in an hour, the loom efficiency depended on the portion of time that the machine was not operating. Such a loom operating at a 75% utilization rate would only produce three yards per hour. The utilization rate depended very much on the skill of the weaver. New weavers might only achieve a 20% utilization rate because they took longer to perform tasks, they caused errors and they failed to detect errors quickly before substantial damage was done to cloth or machine. The utilization rate also depended on the technology and much technical change was realized by increasing the utilization rate of the looms. So utilization is key to understanding the nature of technical change in weaving and also in other mechanized processes.

Engineering Model of Weaving

A simple engineering model is helpful for analyzing the factors that determined the utilization rate and the corresponding capital and labor efficiency of power looms. Utilization is determined by the time required to perform tasks and the frequency with which those tasks need to be performed, measured as the “mean time between failures” (MTBF). This is the average running time before a task needs to be performed. If a loom runs for 5 minutes without other interruptions before a bobbin needs

---

[5] Rick Randall, Exhibit Specialist at Lowell National Historical Park, who operates early twentieth century looms at the museum, wondered how early loom fixers got by without tape. A rough surface on some parts of the loom could cause a shuttle to fly out and he showed me a loom where he had progressively taped over one area after another until he had fixed a persistent problem. Many of these surfaces were covered in leather, which had to be replaced periodically.

to be replaced, then the MTBF is 5 minutes. The MTBF is deterministic in this case, but it could also be the mean time of a stochastic process, e.g., one warp thread breaks, on average, every half hour.

In general, the MTBF for most tasks depends on the speed of operation. If the loom runs faster (more picks per minute), then the bobbin will run out of yarn faster. That is, the MTBF for the *i*th task is $M_i = R_i/s$, where R_i is a constant (in this case related to the amount of yarn on the bobbin) and s is the speed of the loom.

Consider task *i* that is performed while the machine is stopped. Suppose that it takes the weaver T_i minutes to perform the task. Suppose also that the loom sits idle for I minutes on average before the weaver is able to attend to this task. Below I will discuss the nature of these delays. For every M_i minutes of running time, the loom will be down $T_i + I$ minutes for the *i*th task. This means that to produce a yard of cloth, the *i*th task will require $(T_i + I)/(s\, M_i)$ hours of loom time, where s is measured in yards per hour. Given N independent tasks, the total loom time required to produce of yard of cloth is then

$$(1) \qquad X_k = \frac{1}{s} + \frac{1}{s}\sum_{i=1}^{N}\frac{T_i + I}{M_i} = \frac{1}{s} + \sum_{i=1}^{N}\frac{T_i + I}{R_i}\,.$$

Alternatively, the output per loom-hour, that is, the capital productivity, is $1/X_k$ and the loom utilization rate is then actual output per loom-hour divided by the loom capacity speed,

$$(2) \qquad u = \frac{1/X_k}{s} = \frac{1}{1 + s\sum_{i=1}^{N}(T_i + I)/R_i}\,.$$

Task *i* also takes T_i of the weaver's time every M_i minutes. But in addition to tasks performed while the machine is stopped, weavers perform other tasks while the loom is running.[6] I designate the duration of the *j*th of *n* tasks that are performed while the machine is running as t_j. As above, let the mean time between incidents requiring this task (not actual "failure" in this case) be M_j. Then, by similar logic, the weaver time required to produce a yard of cloth is

$$(3) \qquad X_l = \sum_{i=1}^{N}\frac{T_i}{R_i} + \sum_{j=1}^{n}\frac{t_j}{R_j} + W$$

where W is the time (per yard of cloth) that the weaver watches the looms but does not actively perform a task. Below I will explore the determinants of W. Given (1) – (3), output per weaver-hour, y, is

---

[6] For example, after a shuttle was replaced and the loom re-started, the weaver would put a fresh bobbin in the empty shuttle and thread it in preparation for the next shuttle replacement.

(4) $$y = \frac{1}{X_l} = \frac{k}{X_k} \quad \text{and} \quad k = \frac{X_k}{X_l},$$

where k is the (mean) number of looms per weaver.[7] Finally, note that this is implicitly a production function with constant returns to scale. It is quite likely that individual mills experienced some non-constant returns to scale, especially as related to energy production. However, textile firms could and did expand their scale by building multiple mills. In any case, constant returns seems to be the appropriate assumption for a two-factor model.

Capital-labor substitution

Note that this model involves an implicit trade-off: increasing k while holding all else equal, decreases the weaver's idle time, W. But increasing k might well increase the idle time of the looms, I. These machine delays arise mainly because a weaver working on one loom cannot immediately take care of another loom requiring attention.[8] The more looms assigned per weaver, the more likely it is that multiple looms will be down at the same time, leading to idle loom time and decreased utilization rates. That is, there are decreasing returns to k that determine the optimal capital-labor ratio. Alternatively, there is a trade-off between W and I.

The problem I have described here is a standard operations research problem known as a queueing problem with a finite calling population. The characteristics of the model depend on the extent to which the processes causing the looms to stop are deterministic or stochastic. In the purely deterministic case, for example, where a bobbin runs out of yarn after so many minutes of running, the looms can be staggered so that the weaver tends one loom after another in sequence.[9] The performance of this model is shown in Figure 1 by the gray, kinked line. The kink represents the point (k^*) where each loom stops just at the time when the weaver finishes her task on the previous loom. At this point, neither loom nor weaver have any idle time, that is, $W = I = 0$. With $k < k^*$, the weaver has idle time ($W>0$, $I=0$); additional looms increase output proportionally in this range because idle time does not increase. With $k > k^*$, the weaver cannot keep all the untended looms running ($I>0$, $W=0$) and adding more looms just increases idle time; the production function is flat. This, of course, describes a Leontief production function where k^* is the optimal positive allocation of looms per weaver and the elasticity of substitution between capital and labor is zero.

---

[7] I treat k as a continuous variable in the sense that a mill can achieve a non-integer mean allocation of looms per weaver by assigning different numbers of looms to different weavers.

[8] Looms may also be idle without receiving attention from the weaver because they are being worked on by loom fixers or others. I will ignore these tasks in the exposition here.

[9] They will, in fact, converge to such a staggered sequence very quickly regardless of how they were initially started.

When some of the processes stopping the looms are stochastic (for example, weft or warp breaks), then the trade-off is more gradual. I used simulations of models that combined deterministic and stochastic stopping processes for a range of parameters. The data points in Figure 1 show the results of simulation runs using one set of parameters typical of looms for the mid-nineteenth century.[10] This shows some greater substitutability between capital and labor. With stochastic stopping processes, the looms cannot be so neatly staggered, and multiple looms are sometimes idle even when $k < k^*$. As the number of looms per weaver increases, idle loom time, I, increases and idle labor time, W, decreases, but these changes are continuous.

Nevertheless, the substitution of capital for labor is rather inelastic. To estimate the elasticity of substitution, I fit the data points from the simulation runs to a constant elasticity of substitution (CES) production function using Non-Linear Least Squares. That curve for the simulated data in Figure 1 is shown as a solid line. The estimated elasticity of substitution is 0.11 (standard error of 0.018 with adjusted R-squared of .9998). For simulation runs with other parameters, estimates of the elasticity of substitution ranged from 0.09 to 0.15. Below I will compare these estimates to econometric estimates derived from other data.

These estimates confirm the view that weaving technology offered opportunities to substitute capital for labor, but these opportunities were limited and the production function was highly inelastic. Moreover, although the simulation runs used a wide range of parameters, the elasticity of substitution appears to vary only within a narrow range.

Technology and technical change

Examining (1) and (3), technological changes could directly increase productivity by decreasing the duration of tasks, by increasing the MTBF of tasks, and/or by increasing the speed of the machines. Changes in technology might also alter the shape of the production by modifying the trade-off between W and I. For example, an invention might change a stochastic stopping process into a deterministic one; such a change would reduce the elasticity of substitution and it might affect capital productivity by reducing I in the relevant range. However, given the limited variation in the elasticity of substitution, any such changes would seem to have, at best, a small effect on the levels of capital and labor productivity. In analyzing the effects of technical change, I assume, as a first order approximation, that

---

[10] This simulation run was for cloth 48 picks to the inch in the weft, 36 inches across, a loom speed of 130 picks per minute, a task that occurred every time 960 yards of weft were used that took 90 seconds of time while the machine was stopped and 20 seconds while it was running, and a similar task that occurred randomly with a MTBF of 1000 seconds.

I and *W* remain constant when technology changes loom speed or the duration or frequency of tasks.

This means that the direct effect of an invention can be understood simply by the way it shifts the isoquants defined by X_l and X_k. Labor-augmenting inventions (those that reduce X_l) shift the isoquants closer to the origin along the labor axis; capital-augmenting inventions (those that reduce X_k) likewise shift the isoquants closer to the origin along the capital axis. The labor-augmenting bias of a technical change can be defined as

$$\frac{\Delta X_k}{X_k} - \frac{\Delta X_l}{X_l} .$$

It is straightforward to show that labor-augmenting (capital-augmenting, neutral) technical change is Hicks labor-saving (Hicks capital-saving, Hicks neutral) technical change for this model.[11]

Based on (1) and (3), technology imposes some very significant constraints on the nature and direction of technical change. Technical change can occur only in one of three ways, each with a unique technical bias:

1. Reducing the duration and/or frequency of tasks performed while the loom is running. This kind of change reduces X_l but not X_k. This shifts the isoquant along the labor axis, producing purely labor-augmenting technical change.
2. Reducing the duration and/or frequency of tasks performed while the loom is stopped. These changes reduce X_k and X_l by equal amounts. This kind of change augments both labor and capital.
3. Changing the speed of the loom, *s*. This reduces X_k but not X_l, shifting the isoquant along the capital axis and producing purely capital-augmenting technical change.

This classification provides a framework for analyzing the bias of technical change associated with major inventions. It also implies that certain types of inventions are incompatible with some technical biases. For example, if technical change is purely labor-augmenting, as assumed in neoclassical growth theory, then no inventions could automate tasks performed while the loom was stopped and no inventions could increase loom speed.

The next section looks at the actual tasks involved in weaving, the major inventions in weaving, and the associated efficiency gains.

---

[11] Under constant returns to scale, a Hicks neutral technical change is one where the ratio of the marginal product of labor to the marginal product of capital remains unchanged, holding factor proportions constant. This corresponds to the slope of the isoquant remaining unchanged along a ray through the origin. Under the assumption that *I* and *W* are constant, a technical change that augments capital equally in proportion to labor will simply move the isoquant toward the origin, leaving the slope along every ray through the origin unchanged. The argument follows similarly for biased changes.

Nineteenth Century Inventions in Weaving Coarse Cotton Cloth

Efficiency gains

Figure 2 shows labor productivity in weaving for selected mills over the nineteenth century. Looms per weaver is shown on the horizontal axis. Each data point represents a single mill or the average of a group of mills (see Appendix for details). All figures are for cloth that was between 44 and 60 picks to the inch in the weft with a plain weave, mostly shirting, sheeting and print cloths. Cloths are 36 inches wide, or productivity figures are adjusted to be equivalent to 36 inch cloth.[12] Note that these data are only for handlooms (in 1810) and plain power looms, not automatic (Northrup) looms, which were first used in 1895. I excluded Northrup looms because they represented a major, and somewhat expensive, new technology and they were not widely adopted by 1900.[13]

Beginning with handloom weaving, the data points are mostly in chronological order left to right. Handloom weavers performed a number of tasks in addition to weaving, such as creating the warp and dressing the warp (coating it with starch for greater strength) that were not performed by weavers in integrated, mechanized mills. Beginning with the first power looms at the Boston Manufacturing Company at Waltham, Massachusetts, these tasks were performed by separate personnel, often with newly developed specialized machines (Jeremy). For the 1810 data point, I estimate handloom productivity using reported pick and utilization rates for just the weaving process (see Appendix).

Productivity estimates such as these are subject to the vagaries of unmeasured factors. Output at a mill can change dramatically with the level of worker experience, something I explore further below. Output can also vary with a variety of other factors such as interruptions in power at water-powered mills or the skill of loom fixers. Nevertheless, because most of these data points represent averages over long periods of time or over multiple mills, errors from these sources of variation are not likely to be large and variation between mills is not great.[14]

Vertical changes in Figure 2 represent increases in labor productivity. Changes in capital productivity are represented as counterclockwise rotations around the origin. That is, movements along rays through the origin, shown as several dashed lines, are movements with constant output-capital ratios. One such movement occurred mid-century. The rays with steeper slopes represent greater output

---

[12] To adjust output for different widths, I prorate in proportion to figures in the table in Draper (1907), page 170.

[13] Feller's (1966, p. 326) figures indicate that in 1899 the Draper Northrup looms accounted for only 6.5% of the looms in use and many of these were in experimental trials.

[14] For instance, the data point for "1879, water power" covers 6 mills and the 95% confidence interval around the mean of 18.7 yards/weaver-hour ranges from 16.3 to 21.0.

per loom.

Figure 2 also shows, at the top, some major inventions and when they were implemented relative to the benchmark mills. Generally, the inventive activity falls into three periods: in the early century, a cluster of inventions complementing the early power looms increased both loom speeds and the number of looms per weaver; during mid-century, there were few inventions and little change in output per loom, but increases in looms per weaver; and from about 1870 on, when increased use of steam power and complementary inventions increased both loom speeds and looms per weaver. I will discuss the inventions in greater detail in the next section.

Overall, output per loom increased almost four fold while looms per weaver increased seven fold. Part of this capital deepening surely arose from factor substitution, but only a small part. During the same period, unskilled wages increased by a factor of 2.3 (David and Solar 1977), while capital costs remained roughly the same (see below). Given an elasticity of substitution of 0.15, this suggests that changing factor prices account for an increase in the number of looms per weaver of only 12%, which corresponds to about 6% of the total capital deepening. The rest had to come from a technical bias. With numbers like these in weaving and similar numbers likely in other technologies, it is not hard to see why Hicks and others might have concluded that inventive activity had a strong labor-saving bias. So I look next at the major inventions in weaving.

Weaving tasks and inventions

What gave rise to this apparent labor-saving bias? Table 1 lists the major tasks involved in weaving and the major inventions that addressed these tasks. In addition, the table lists inventions that increased the speed of the looms, also shown at the top of Figure 2 at the point they were implemented.

This list of inventions corresponds closely to those inventions mentioned by contemporaries and historians as being important in coarse cotton cloth production (Barlow 1878, Copeland 1912, Draper 1907, Fox 1894, Gilroy 1844, Harriman 1900, Hayes 1879, Jeremy 1973, Macmillans1862).

Aside from the mechanization realized by the first power looms, the major inventions that influenced nineteenth century productivity are, briefly:

- Automatic let-off adjustments adjusted the tension on the warp which would naturally change as the diameter of the warp remaining on the beam diminished, reducing the time a weaver needed to spend making this adjustment. An early friction-based mechanism was employed in Lowell in 1835 (Lazonick and Brush 1985 p. 88, Montgomery 1840, p. 103). Later improvements included the “Bartlett” and “Roper” letoff motions, however, while these offered some advantages, they were not universally adopted and many weavers preferred the friction mechanisms at the end of the nineteenth century (Hawkesworth 1896, Draper 1903).

- Handloom weavers used a device to keep the sides of the cloth, called "temples," from pulling in. These had to be reset frequently. A self-acting (automatic) temple developed by Ira Draper was successfully employed in Waltham in 1825 (Hayes 1879, p. 42, Jeremy 1973).
- The "protector" (also called "stop rod" and "frog-and-dagger") automatically stopped the loom if it detected that the shuttle was not where it was supposed to be immediately after the pick. This prevented many "smashes," where a shuttle stuck in the cloth is struck by the reed, possibly breaking hundreds of threads. First patented by Gorton in 1791 (Barlow 1878, p. 264) this was employed in looms from 1796 in the U.K. This device was likely employed in most early U.S. power looms.
- The "weft fork" detected whether the bobbin had run out of yarn or the weft yarn had broken; if so, it stopped the loom. Prior to this invention, the loom would continue to run and weavers would have to take time to back it up (possibly hundreds of picks). Although first invented in the 1830s (Barlow 1878, p. 262), it was apparently not widely used in the US (mainly in new looms) until the 1870s (Burke 1876, Hayes 1879, p. 42, Draper 1907, p. 28).
- A significant number of inventions allowed increases in machine speed. In general, two sorts of factors limited machine speed: the cost of energy[15] and greater risk of damage to cloth, machine and weaver at higher speeds. Energy costs decreased sharply over time especially with improvements in steam engines and water turbines installed after 1870 (Crafts 2004, Atack et al. 1980).[16] But while lower energy costs may have made faster speeds economical, they were accompanied by critical complementary inventions that reduced the associated increase in machine errors (e.g., flying shuttles), machine wear and tear, and risk of injury to weavers. In 1828, Moody increased looms speeds by changing the power delivery from English-style gearing to belt drives (Gibb 1950, pp. 76-8). Several contemporary observers attribute increased loom speeds after 1860 to the friction brake, which reduced machine wear and tear when the loom was stopped (Fox 1894, Hayes 1879, Watson 1863). Yet the friction brake was surely

---

[15] Lyons (1987) suggests that energy costs increased as the square of loom speed, so these could increase rapidly beyond a certain point. It appears that in practice, these costs were offset by improvements in machine power efficiency. Bourne (1865) reports that a calico loom running 105 picks/minute in 1865 required about 0.1195 horsepower. Fish (1896) reports that at the end of the century, with looms running about about 160 picks/minute on similar cloth, looms required about 0.1801 horsepower. This is an approximately linear increase.

[16] The In 1840, Temin (1966a) estimates that about 85% of cotton mills used water power. In 1870 67% of power supplied to cotton mills was water power; by 1905, only 24% was (Copeland 1912, p. 28, fn. 2).

complemented by reduced power costs that made it more economical to run at higher speeds. Atack et al. (2008) find that labor productivity was higher at steam-powered mills in all industries during this period, but they are unable to distinguish to what extent steam permitted faster machines speeds and to what extent steam plants were newer and thus had more productive vintages of equipment.[17] Other improvements facilitating faster loom speeds in the latter half of the century include the parallel picker motion (which propelled the shuttle more accurately and with less power required), shuttle guards (which protected against shuttles flying out), and generally sturdier machine construction (which permitted machines to run at higher speeds with fewer errors or accidents).[18]

Several other inventions that did not appear to have a substantial impact on nineteenth century productivity were the precision take up motion (which allowed more precise control of the number of picks per inch, thus improving cloth quality), the Northrup loom and Barber warp tying machine (both of which were not widely implemented until the twentieth century), and warp stop motions (which stopped the machine when warp threads broke). While warp stop motions were deployed during the latter nineteenth century at some mills, much of this production was in fine cloths (Harriman 1900). Moreover, where it was employed in coarse cloth production, productivity gains appear to have been largely offset by the added labor needed to draw and dress the warp (Young 1902).[19]

Table 1 also shows rough estimates for the increases in loom and weaver efficiency realized by each invention at the time it was implemented. These are crude calculations based on estimates of task duration and MTBF obtained from historical accounts by manufacturers and equipment suppliers, from weaving manuals, and from measurements taken on working museum models and interviews with museum personnel.[20] In the Appendix, I detail the estimates of these quantities. I calculate the

---

[17] New mills and renovated mills likely used the latest loom technology, while older mills that did not upgrade their power supplies likely used older loom technology as well. When water-powered mills in Lowell, for example, upgraded their equipment, they supplemented their water power with steam engines to provide power during those times of the year when water power was insufficient. For example, I find that mills powered exclusively by water in 1879 had about the same output per loom as mills in 1835 (see Figure 2); steam-powered mills had greater output per loom and mills powered by a combination of steam and water had an intermediate output per loom. It seems very likely that most of the mills powered exclusively by water power did not use the weft fork, which would have increased utilization. On the other hand, Boott Cotton Mills, Mill No. 1 *did* use the weft fork in 1876, and it did have higher output per loom (Burke 1876). It also had an improved power system then.

[18] Much of the framing of the early machinery was made of wood (Montgomery 1840, p. 110); later it was largely metal.

[19] Young (1902) reports on a variety of mills, some using warp stops and some not, for the reasons mentioned. Warp stops required threading each warp thread through a loop. This took time and also increased the likelihood of warp breaks; mills using warp stops had to dress the warp more heavily to counter this tendency.

[20] For these I thank Rick Randall at the Lowell National Historical Park and also Mike Christian at the American Textile History Museum in Lowell.

efficiency gains, assuming that W and I remain unchanged, as $-\Delta X_k/X_k$ and $-\Delta X_l/X_l$.

The values of task duration, frequency and speed very likely varied considerably from mill to mill. Consequently, my estimates of efficiency gains would have varied as well. To test the validity of the figures I used, I calculated the output per loom ($1/X_k$) for several of the benchmark mills fixing $I=0$. These are shown, along with the actual output per loom, in Table 2. As can be seen, the numbers correspond reasonably well, suggesting that my figures are correctly capturing loom utilization rates to the first order and that the implied values of I are reasonably small (they range from 1 to 9 seconds).

The efficiency figures are calculated using data from the benchmark mills at the time the inventions were first implemented. This is an important qualification. Given the interdependencies implicit in the engineering model, the calculations would have been quite different if done at a different date. In a sense, some of the earlier inventions may have made later inventions feasible. However, since the induced innovation hypothesis concerns the gains that mill owners would have expected to get in the short to mid-term, we want to obtain estimates that correspond to those expectations.[21] This qualification is also important because weaver skill levels changed dramatically over time, as I explore below, and the average skill level has a strong effect on realized productivity.

The data in Table 1 suggest several conclusions. First, inventors found improvements for almost *every* aspect of weaving. Every task except removing the finished cloth and cleaning was an object of inventive activity during the nineteenth century. As Salter (1960) argued "any advance that reduces total cost is welcome; whether this is achieved by saving labor or saving capital is irrelevant." This means that technological considerations necessarily played a strong role in determining the technical bias of inventions with factor prices necessarily playing a smaller role.

More generally, the pattern of efficiency gains shown does not seem to strongly favor labor efficiency over capital efficiency. Surprisingly, the combined gain in loom efficiency for the inventions shown is an increase of about 275% (that is, almost a four-fold increase). Although not directly comparable,[22] this roughly corresponds to the gains in capital efficiency observed in Figure 2. However, the combined gain in labor efficiency was only 359%, only modestly higher than the rate of capital augmentation. Comparing these two efficiency gains yields a labor saving bias of 84% (359% -

---

[21] In the induced innovation models, firms choose new technologies (or invest in the development of new technologies) with regard to expected discounted profits based on expected factor prices. This means that they are mainly concerned with the profits and prices expected in the decade or so after adoption, regardless of how technology gets used decades later.

[22] Because of the interdependencies of the various components of total efficiency, this figure, calculated by multiplying one plus the efficiency gain from each invention, does not directly correspond to the total efficiency gained.

275%). This implies that the labor saving bias of these inventions accounts for about a doubling of the looms per weaver—far less than the seven-fold increase observed in Figure 2. There seems to be something missing, which I will explore in the next section.

This result seems surprising because, despite what has been widely assumed since Hicks, these *inventions* do not seem to exhibit a strong labor-saving bias in weaving, at least as the inventions have been first implemented. However, such a conclusion might be bit premature for two reasons. First, had the period of study been a few decades longer, the Northrup loom would have been included and this invention was likely strongly labor-saving. Nevertheless, it is striking that the cumulative effect of the inventions implemented during the nineteenth century was not strongly labor-saving and does not seem to account for much of the gain in capital intensity then. Second, the measure I use does not adjust for the *quality* of capital. That is, the growth in efficiency per loom will overstate the growth in capital efficiency if the looms of 1900 cost more to build than the looms of 1800. Next I look briefly at whether capital quality will alter the basic conclusion.

Capital quality

The power loom and its associated power generation and transmission capital certainly cost more than the handloom. However, it turns out that the difference in capital costs per loom between 1900 and 1800 was small because the greater capital requirements of power weaving were offset by technical advance in the construction of looms, energy equipment, and buildings.[23]

Table 3 shows estimates of capital costs for weaving per loom in 1836 and 1900. Shelton (1986, p. 51) estimates that handlooms cost from $60 to $150 in 1820. Power looms did not cost much more. Patented Waltham looms cost outsiders $150 in the early years, but was sold for $125 in 1823 and $80 in 1830 (Mohanty 1989, fn. 27). The Gilmour loom, which was sold competitively, was $75 and this is the figure Montgomery uses in his 1836 calculations (Montgomery, 1840, Nourse 1903, p. 44).[24]

The power looms of 1900 had many improvements, however, many of these were not costly to produce. For example, one invention, Graham's picker motion, added only 45.5 cents to the $59.63 it cost to build a loom (*Mason v. Graham*, 90 U.S. 261, 1874). But the big difference was that improvements in machine-building technology such as machine tools dramatically reduced the cost of

---

[23] I want to include technical advance in the creation of the capital in my final efficiency estimates because I am concerned about the overall direction of technical change in this technology, not the technical change in weaving firms per se. For this it does not matter if the advance occurred in a weaving firm or in an equipment manufacturing firm.

[24] Prices for hand looms were also close to prices for power looms in the United Kingdom during the early nineteenth century. Handlooms cost £7-10 (Landes 1969 p.65, fn. 1), while a power loom cost £9 (Montgomery 1840, p. 209).

building looms (Chapman and Butt 1988). McGouldrick's (1968, p. 240-1) index of machinery cost per spindle declined from $27.97 in 1827 to $9.58 in 1886. Thus it is not surprising that Young (1902) reports loom costs in 1902 of $56 and $58—less than the cost in 1836 despite the many improvements. Uttley (1905, p. 66) reports a loom cost of $40.58.

Similar efficiencies were realized in the cost of power and buildings. Power costs of 1900 (capitalized) were about 30% of their 1836 level;[25] mill building costs were about 54% of their 1836 level.[26]

Table 3 compares these estimates for hand and power looms. I estimate the capital costs for handloom weaving to be just over $100 per loom. This estimate may be a bit low: using reports from weaving sheds (without spinning and excluding power looms) in the 1820 Census of Manufactures, I find a mean quantity of capital invested of $137. Comparable capital costs for power looms in 1836 are much higher, at about $169. But despite many added improvements and many improvements in machine construction, the power looms of 1900 had capital costs just about equal to the capital costs of handlooms at the beginning of the century; less, if one takes Uttley's figure for loom cost. These figures are in nominal dollars; using the GDP deflator, the 1900 figures would be 3% lower in 1836 dollars.

Thus, even taking a capital quality adjustment into account, the inventions in nineteenth century weaving do not exhibit a large labor saving bias. Nevertheless, the benchmark data in Figure 2 suggest an overall increase in labor efficiency greater than what can can be explained by the listed inventions. But what then explains the discrepancy? Something must have caused the seven-fold increase in looms per weaver. I now explore possible explanations for this apparent discrepancy.

Labor-saving and individual workers

A major part of this puzzle seems to concern a period of several decades during mid-century. As noted above, during mid-century, the number of looms per worker grew steadily, the capital-output ratio remained more or less constant, and there were no major inventions listed. The increase in looms per worker at that time explains a large part of the discrepancy between the overall growth in looms per worker in Figure 2 and the labor efficiency gains reported in Table 1. But what caused this growth?

I will explore four possible explanations:

---

[25] Using the mid-range of Atack et al.'s (1980) simulation estimates, steam power costs were at 28% of their 1840 level in 1890 and water power costs were about 35%. Using Craft's (2004) estimates for Britain, steam power costs in 1910 were 20% of their 1830 level.

[26] Using McGouldrick's (1968) building cost index for 1836 and 1886.

1. the growth in the capital-labor ratio was actually substitution of capital for labor along the production function,
2. some inventions are not included in Table 1,
3. the "stretch out" forced workers to exert greater effort,
4. and increasing worker skills (endogenously determined) permitted greater capital intensity.

To do this, I use detailed data on worker productivity in a single mill, specifically the Upper Weave Room in Mill No. 2 of the Lawrence Company in Lowell, Massachusetts. These data were originally transcribed by Lazonick and Brush (1985) from payroll records. They include monthly output for each worker on piece rate or days on dayrate, earnings and some information on worker characteristics such as whether the weaver could sign her name. These data are available monthly from December 1833 through December 1855, although some months are missing and others I excluded because they were known to be months with insufficient water power.[27] The Upper Weave Room had 144 power looms throughout this period. The Lawrence Company appears in Figure 2 as the data points for 1835 and 1855; the looms per weaver increased from 1.8 to 3.4 during this period, with a corresponding increase in labor productivity.

Factor substitution

Could the capital deepening be explained as substitution of capital for labor among previously known techniques, despite my low estimates of the elasticity? At first sight, this does not seem to be a good explanation because movements along the production function should theoretically involve diminishing returns to capital. Yet output per loom remained more or less constant during this period—during 1835 the mill produced 3.9 yards of cloth per loom-hour; during 1855 it produced 3.8 yards per loom-hour. It is possible, of course, that diminishing returns were accompanied by increases in capital efficiency that just happened to offset them. I explore this possibility in the next section.

The engineering model found a low elasticity of substitution, implying a small role for factor substitution, but perhaps this model is wrong. To test it, I fit a CES production function to monthly data for Lawrence Mill No. 2 using a specification first used by David and Van de Klundert (1965). Assuming a constant elasticity of substitution, σ, a constant rate of labor augmentation, g, and a constant rate of capital augmentation, z, then output per weaver at time t is

---

[27] I thank Lazonick and Brush for sharing their data with me. Productivity is not recorded for workers paid on a day rate, who were mostly new workers during the first few weeks of learning the job. To calculate the productivity of workers on day rate, I pro-rated the aggregate output of the weaving room (recorded in account books) after deducting the output of piece rate workers to arrive at an estimate of 1.79 yards per day for dayrate workers.

$$(5) \qquad \ln y = -\frac{\sigma}{1-\sigma}\ln\left((e^{zt}k)^{-\frac{1-\sigma}{\sigma}} + a\,e^{-gt\frac{1-\sigma}{\sigma}}\right) + b\cdot$$

I estimated this production function using Non-Linear Least Squares, excluding months where water power was known to be insufficient. I also excluded the first six months of operation of the mill because learning-by-doing strongly affected productivity (David 1975). The estimates are shown in Table 4. The estimates show a clear labor-saving bias (that is, $g > z$) and an elasticity of substitution of 0.142. This estimate is quite close to the estimates obtained from the engineering production model which ranged from 0.09 to 0.15.

These estimates also correspond well with Asher's (1972) findings. Asher estimates the elasticity of substitution for the entire US cotton industry (not just weaving) from 1850 – 1900 using a CES production function with constant rates of capital- and labor-augmenting technical change. He obtains estimates of the elasticity of substitution ranging from 0.04 to 0.15.

With such low elasticities, factor substitution can only explain a small fraction of the increase in capital deepening. The hourly wage of weavers in 1855 was only 9.6% higher than in 1835. Ignoring the difference in skill levels, which I argue below was quite substantial, and changes in capital prices (capital was sunk), this implies that factor substitution increased the capital-labor ratio by only 1.3%.[28]

Finally, direct evidence from Lawrence Mill No. 2 shows that the transition from two loom per weaver to three loom per weaver was hardly a costless switch from one known technique to another. Figure 3 shows the mean monthly output per loom-hour for the Upper Weave Room during the early 1840s. Faced with a depression in early 1842, the mills in Lowell began experimenting with different numbers of looms per weaver and different loom speeds (Dublin 1979, p. 109). Shortly thereafter, they switched to three looms per weaver (Montgomery 1843, p. 132). Based on the payroll records of the Lawrence Company, this change was made permanent from June on. Montgomery notes (p. 132) that weavers had difficulty keeping up with three looms and so the mills slowed loom speeds by about 15%. Figure 3 clearly shows this drop. However, over time weavers apparently learned new ways of handling more looms so that in about a year and a half the original loom speeds were restored and output per loom-hour pretty much returned to previous levels.

This loss of output indicates that the transition to three looms per weaver was not costless; the lost productivity per loom implies an opportunity cost. I explored the role of individual learning at the Lawrence Company and its associated costs in an earlier paper (Bessen 2003; see also David 1975 for a

---

[28] Even using Margo's (2000) index of wages for unskilled male workers, wages increased by 23% from 1835 to 1855, corresponding to a 3% increase in the capital-labor ratio.

discussion of mill-level learning-by-doing). Weavers would begin at very low levels of productivity and, over a period of six months or longer, would improve, rapidly at first and then more slowly. Figure 4 shows average labor productivity by month on the job for two cohorts of workers, one from 1833-6 when weavers were assigned two looms, and one from later years when weavers were assigned three or four looms each. This increase in productivity corresponds to an increase in loom utilization. The engineering model suggests that utilization would increase as workers could perform tasks faster. But note also that the later cohort, tending three or four looms, took longer to get up to speed. Learning was slower for this cohort perhaps because they had to also learn to better anticipate problems, detect and fix them early, before they could do much damage, and to better coordinate their activities on each loom. This additional learning explains why in 1842 even experienced workers had difficulty keeping up with three looms at first, but were eventually able to do so over time.

In any case, this transition was not a costless movement along a production function. It appears to have involved the learning of new techniques and new skills as opposed to a transition to previously-known capital intensive techniques.

Exogenous technical change

But how much of the increase in labor efficiency could be attributed to learning on the job and how much arose from exogenous improvements in the technology? Perhaps I have missed important inventions that were implemented mid-century.

First, both historians and contemporary observers have noted that weaving experienced strong technological change during the early decades of the nineteenth century and/or the late decades, but not during the middle decades. Gibb (1950), Jeremy (1973) and Strassman (1959) stress the remarkable improvements made in the early decades relative to later decades. Draper (1907), Hayes (1879) and Harriman (1900) note the improvements made at the end of the century after a period of relative stagnation. Habakkuk (1962) argues that historians ascribe “the absence of technical progress in the American textile-machine industry between 1840 and 1870 to the softening effect of abundant demand.”

It is true that there was significant *inventive* activity mid-century, but many of these inventions were not widely employed for decades, many not until steam power was widely used. For example, Gilroy claims the first weft fork in England in 1831 (Barlow 1878, p. 262; multiple inventors claimed this invention) and it was patented in the U.K. by Ramsbottom and Holt in 1834. But although it was used at refurbished mills during the 1870s, it was not used by the late 1830s in the U.S. (Burke 1876, Draper 1907, p. 28, Hayes 1879, p. 42) and it apparently was not used at most water-powered mills even in the 1870s (see fn. 17 above). The friction brake was applied to the weft fork in 1842 by Bullough in the U.K. A friction brake was patented by Bigelow in 1856 in the U.S. (U.S. Patent No. 14,590). This invention was credited with increasing loom speeds, but apparently was not widely deployed until the 1870s, especially at new or renovated mills which began to realize significant economies in power costs.

It is possible, of course, that there were a number of minor inventions, too insignificant to receive mention in contemporary accounts, but which had substantial cumulative impact on productivity. Loom fixers would often tinker with the machines, making minor improvements. However, the model of loom used in the Lawrence Company Mill No. 2 had been used for around ten years, so it seems unlikely that many minor improvements of that sort would not have been previously tried and adopted before 1835. Searching the documentary record, Lazonick and Brush (1985) identified only two changes that might have affected productivity at the Lawrence Company: in May 1835 the looms were retrofitted with an automatic tension adjustment (which is included in Table 1) and in August 1844 a change was implemented in a preparatory process (an improved cotton picker) that may have improved cotton quality in weaving. But aside from possible retrofitting, the same looms were used until 1867 (McGouldrick 1968, p. 229).

To test for possible unobserved inventions, I ran a regression on individual weaver output with a term for learning based on the weaver's experience, x, and residual year dummies to capture any trend on productivity. I measure experience as days worked plus a dummy term for workers who had previous experience.[29] I assume that the gap between inexperienced weaver's utilization rate and their ultimate utilization rate can be approximately fit by a declining exponential function where the rate of decline decreases with the number of looms per weaver:

$$\ln y = \ln k + \ln(1 - e^{-\beta x k^{-\alpha}}) + \ln \delta_t + \theta \cdot Z \tag{6}$$

where the δ are year dummies and Z is a vector of other dummy variables. Table 5, Column 1 shows that this specification does have a close fit. However, between 1835 and 1855, the residual only grew at about 0.01% per annum, not statistically or economically different from zero.[30] The second column

---

[29] I am able to detect if a worker had previous experience by observing whether the worker began employment on piece rate. Workers without previous experience would spend several weeks training on a day rate (see Bessen 2003). I measure effective experience = days worked + γ I[previous experience] where I is 1 if the worker had previous experience, 0 otherwise, and γ is an estimated parameter.

[30] I do not include the time dummies for 1834 and December 1833 because there was possible learning or other adjustments at the mill while new production was ramped up.

adds month dummies and dummy variables for the two technical changes reported by Lazonick and Brush (1985). Together, these dummies account for a 7% increase in productivity, but this is offset by a declining residual.[31] Note that the first dummy represents the retrofitted automatic let-off tension adjustment that is included in Table 1 with an estimated increase in labor productivity of 3%. Column 3 adds dummies for weaver characteristics (whether the weaver could sign her name, Yankee ethnicity, and whether the weaver had a gap in her employment) and an index of cotton quality from Lazonick and Brush. Still, the results are similar. Once learning on the job is taken into account, technical improvements not listed in Table 1 only account for about a 7% increase in productivity at most, or about 0.3% per annum. However, actual labor productivity growth from 1835 to 1855 was 2.9% per annum. Unobserved inventions do not seem to account for much of this productivity growth.

Note that the residual in this regression only captures improvements reflected in the loom utilization rate. Unobserved inventions could still play a more significant role if they were purely labor-augmenting, that is, if they reduced the duration or frequency of tasks that the weaver performed while the loom was running. If this were the case, such inventions might permit the weaver to handle more looms, thus increasing productivity without affecting the utilization rate. However, I estimate that these tasks only took about three minutes of every hour for a weaver tending two looms after 1835.[32] So even if these tasks had been completely automated by some unmentioned invention, they could not account for much of the increase in labor productivity. In fact, these tasks were automated by the Northrup loom at the end of the century.

Effort

Some historical accounts of Lowell (Ware 1931, Josephson 1949) have stressed that the "stretch out" (increase in machines per worker) amounted to exploitation of the weavers—tending three looms instead of two required them to exert greater effort. Perhaps weavers increased their output simply by working harder. There are several problems with this explanation, however.

First, the drop in output per loom seen in Figure 3 seems at odds with this story. Presumably, weavers would not have exerted more effort unless they had incentives to do so, such as greater pay or greater risk of getting fired if they failed to do so. From this perspective, adding a third loom offered the weavers an opportunity to make more money by working harder. Piece rates remained unchanged

---

[31] Only the second dummy variable is statistically significant and only at the 5% level. Lazonick and Brush (1985) and Bessen (2003) find no statistically significant improvement from these changes.

[32] After the automatic let-off motion was employed in 1835, these would mainly consist of replacing the empty bobbin in the spare shuttle and threading the weft thread through that shuttle.

for several months, dropping only in August of 1842 and then again in January of 1843. Even then the piece rate was only 28% lower than in early 1842 even though capital per weaver had gone up 50%. Thus the additional loom may, indeed, have motivated weavers to work harder; the greater capital at their disposal would have given them the opportunity to earn more.[33]

However, if the increased productivity were simply a matter of greater effort elicited by greater incentives, then one would expect the greatest effort—and hence the greatest labor productivity—to be exerted when the piece rate was the highest, in June and July of 1842, and to decrease after that. In fact, labor productivity does not exhibit any distinct trend until an increase is seen in early 1844 (after the weavers had acquired greater skill). Although the weaver tending three looms may well have exerted greater effort (both at learning and, later, operating the looms), it appears that this greater effort could only be fruitfully exerted after the weavers had increased their skill level over time.

Could the initial drop in productivity have been the result of a labor slowdown? It is possible that even though the weavers' individual incentives were greatest at first, if they were highly organized, they might have undertaken a collective slowdown in anticipation of future decreases in the piece rate. But this explanation seems questionable. First, there is no evidence that the weavers were highly organized and previous, spontaneous walkouts had failed. Second, it makes little strategic sense to organize a slowdown until piece rates had actually been cut. But, in fact, there was no decrease in productivity following piece rate reductions in August and December of 1842.

Ware and Josephson buttress the exploitation story with a cultural explanation. They suggest that greater exploitation was possible in the 1840s and 1850s at Lowell because the literate Yankee girls who were hired as weavers during the early years were replaced by "low class" Irish immigrants who were often illiterate. According to this explanation, the Irish girls would be less able to resist the mill owners' efforts to force them to work harder and to cut their pay. However, the evidence suggests that the Yankee mill girls were no less able to resist any such intensification of work or reduced wages. They had accepted pay cuts (although one, in 1834, prompted a brief and unsuccessful walkout) and the stretch out in 1842 was accepted by a workforce that was still 95% Yankee and literate. So ethnic background does not explain the productivity increases realized during the early 1840s. However, as I argue elsewhere (Bessen 2003), the development of a local labor supply, which was largely immigrant, did facilitate greater investment in on-the-job skill development.

Clark (1987, 2007) has echoed this cultural explanation with a twist. Making international

---

[33] And to the extent that they could keep up with three looms, as they increasingly did from 1844 on, they had an opportunity to earn a greater share of output (not exactly exploitation).

comparisons, he finds that some nations (e.g., the U.S. and U.K.) deployed many more looms per weaver at the beginning of the twentieth century than others (e.g., India, China, Japan). Figure 5 shows some comparisons similar to Clark's for comparable cotton cloth production (about 50 picks/in, simple weaves, 36 inches wide) in different nations during the first decade of the twentieth century. This figure shows the same axes as in Figure 2, but the data are from a single point in time. As Clark discusses, all nations used more or less the *same* looms, almost all supplied by U.K. manufacturers, except for the U.S., where the looms were similar.

Comparing Figure 5 to Figure 2, it seems that on-the-job learning might have something important to do with the international differences. All of the looms were operated at roughly similar speeds—the data points cluster around the ray through the origin.[34] But weavers in some nations operated more looms than in others, just as US weavers handled more looms in 1879 than they did in 1835. On the job learning provides a parsimonious explanation for this pattern that is consistent with the evidence for the U.S. during the nineteenth century. Clark argues that workers in the higher productivity nations simply worked harder, however, although Clark considers experience as a factor, he does not consider learning on the job, as I have treated it here.[35]

Endogenous skill development

Montgomery noted that the weavers could not keep up with the looms when they were first given three to handle in 1842 (Montgomery 1843, p. 132). For this reason, the mills temporarily decreased the speed of the looms. However, as Figure 3 shows, the weavers were able to handle three looms at the original speed a little over a year later. What changed?

If the decision to increase the looms per weaver had been made as a simple choice of new technique—either a previously known technique or an innovation—then weavers would not have had trouble keeping up, unless there were new technical knowledge or skills to be acquired. Nor does it

---

[34] Looms in the UK ran a bit faster than those in other countries including the US. Several reasons have been discussed for this. The UK had lower energy costs than the US, prompting more energy-intensive production. Copeland (1912, p. 90) notes that UK union resistance to more looms per weaver prompted mills to achieve greater productivity through faster operating speeds. UK looms cost relatively less to construct, perhaps making more rugged looms less expensive in comparison. Young (1902) highlights some of the differences between U.S. and U.K. looms. The most important speed-related difference appears to be the heavier construction of U.K. looms. Copeland (1912, p. 89) claims that the over-pick style of the English looms (the picking motion above the warp) allowed them to run faster. However, U.S. looms were certainly capable of running at faster speeds and there seems to be little technical reason (based on discussions with Rick Randall at Lowell) that an under-pick loom would be slower in principle, especially after the introduction of the parallel picker motion in the 1850s.

[35] In the next sub-section I explain why experience is not a good proxy for learning.

seem that weavers were simply “resisting” the “stretch-out” a first, only submitting later; it would have made more sense for them to conduct a slowdown when piece rates were actually cut, not before. On the other hand, on-the-job learning provides a parsimonious explanation consistent with the observed facts: the duration of the learning period and the magnitude of foregone output are consistent with observed learning curves and the economics of learning provides an explanation as to why the transition occurred in 1842 and not earlier or later.

Figure 3 shows that the transition to three looms per weaver involved about a year or so of decreased capital productivity followed by a return to the previous level of output per loom. Handling an additional loom would have placed a premium on the weaver’s ability to anticipate loom stoppages and other problems, to detect and fix errors more quickly and to coordinate activities between the looms more efficiently. These skills and the associated technical knowledge would have taken some time to develop. The learning curves for new hires after 1842 shown in Figure 4 and the coefficients in Table 5 show that weavers face a longer learning period when they tend additional looms. Figure 4 and Table 5 also imply that this learning would have taken about a year, more or less, as it did.

Also, the opportunity cost of evident in Figure 3 is about 15% of one year’s output per loom. This compares closely to an estimate of 18% based on the results of foregone output for training new weavers on two and three looms.[36] Thus learning provides an explanation of the mid-century capital deepening and the associated increase in labor productivity that is fully consistent with both the observed duration and magnitude of the foregone output.

Although learning takes time and is thus associated with weaver experience, it is important to distinguish learning from experience. It is common to equate worker experience with human capital acquisition.[37] However, the learning at Lowell occurred only for a limited period of time and only under certain conditions. This makes job tenure a poor proxy for human capital acquired through learning.

Moreover, this learning depended on an explicit decision by the mill owners to allocate more looms per worker. A majority of the weavers employed in June 1842 had already acquired significant experience, but they were only just then given the opportunity to develop new skills on three looms over an extended period of time. But this decision by the mill owners involved a significant opportunity

---

[36] Using data from Bessen (2003, Table 1), the foregone output for training a worker on 2 looms is 2,783 yards and is 10,502 yards on 3 looms. Pro-rating this difference across 3 looms, and dividing by annual output per loom is (10502-2783)/3/(12.5*300*3.83) = 18%. Of course, retraining an already experienced worker is a somewhat different exercise, yet the magnitude of the foregone output is reasonably similar.

[37] For example, Clark (1987) considers and rejects worker experience as an explanation for international differences in looms per worker.

cost: the mills suffered a significant loss in output, compared to levels achieved with two looms per weaver, while the weavers acquired their new skills. That is, this decision required a human capital investment in the form of foregone output.

In an earlier paper (2004), I calculated the magnitude of these investments and I showed that three looms per weaver was advantageous in 1842 compared to two looms, however, three looms were not advantageous earlier. Two things had changed by 1842 to make the extra investment worthwhile: 1.) cloth prices had dropped substantially (relative to wages), reducing the cost of the output foregone while the weavers were learning, and, 2.) the mills were able to retain an experienced workforce longer, providing a longer period of time for the mills to recoup their human capital investment.

The mill owner's decision can be readily modeled in a more general way from equation (6). Assume that each worker stays employed for T periods and is paid a wage of w and that p is the shadow price of weaving (exclusive of material costs, etc.). Then maximizing the mill's profit yields an optimal number of looms per weaver (see Appendix) that is related to wages and prices,

$$(7) \qquad \ln\hat{k} \propto \ln\frac{wT}{p}$$

This shows that the number of looms per weaver was *endogenous.* Mill owners decided the capital intensity of weaving in part based on prices and wages (and job tenure). That is, my evidence supports Habakkuk's (1962, p. 47) thesis that factor prices influenced "the training that the American manufacturers gave their workers so that each was able to handle more looms." English weavers, with lower wages, would be assigned fewer looms. Once U.S. weavers began handling more than two looms in 1842, they handled more looms than their English counterparts through the end of the century, as seen in Figure 5.

This is, of course, not the usual way Habakkuk is interpreted and the quote above suggests some ambiguity in Habakkuk's thinking. The endogeneity I find here comes not in the choice of innovations, but in how the innovations were implemented. Moreover, in my model the ratio of wages to output price determines the optimal number of looms per weaver, not the ratio of wages to capital costs. Relative capital costs may well influence the choice of innovations to some extent. However, the evidence from nineteenth century weaving suggests that endogenous learning accounts for most of the observed labor-saving bias, not inventions.

Accounting for the Growth in Labor Productivity

Accepting this interpretation, it is possible to decompose the annual growth in output per worker roughly into contributions from different sources as shown in Table 6. I calculate the contribution from factor substitution as the rate of growth of wages relative to capital costs times the output elasticity of capital (estimated by the capital share of output) time the elasticity of substitution (see Bessen 2008 for a formal derivation).

Between 1835 and 1855, labor productivity in the Upper Weaving Room grew at 2.9% per year. My analysis suggests that almost all of this increase arose from technical change. Even though capital per worker nearly doubled, only about 0.1% of this growth in labor productivity can be attributed to capital substituting for labor, leaving a rate of technical change of 2.8%.[38] Of this, the annual contribution from inventions and other changes appears to be no greater than 0.3%[39], leaving a large share to the acquisition of skill and technical knowledge on-the-job.[40]

These two decades, however, are not representative of the entire century. The contribution from factor substitution is similar, no more than 0.1% per annum.[41] Table 1 suggests that over the whole century, inventions contributed at least a four fold increase in labor productivity, equivalent to a 1.5% per annum rate, compared to approximately a 3.2% per annum growth in labor productivity. Some inventions may have also been skill-saving, making the contribution of inventions even larger.[42] If one allocates to "endogenous learning" only the increase in productivity associated with the growth in looms per worker from 1835 to 1879 (from 1.84 to 5.1 looms per worker on average), then the contribution from endogenous learning is only 1.0% per annum, leaving 2.1% per annum to inventions and other changes.

The overall picture is that technical change, not factor substitution, accounts for almost all of the growth in labor productivity and a substantial part of technical change—one third to one half—arises not from inventions but from the acquisition of technical knowledge and skills by workers on the job.

Note that the rates of growth I attribute to technical change are larger than estimates of TFP

---

[38] The 1.3% increase in the capital-labor ratio attributed to substitution above, prorated over 20 years corresponds to a 0.067% per annum increase in looms per worker. Using Margo's (2000) wage series (see fn. 28), this would be a 0.2% per annum increase in looms per worker. Multiplying this growth rate times the capital share of output (see Bessen 2008), yields at most 0.1% using the most optimistic figures.

[39] The last column of Table 5 shows about a 7% gain over 20 years associated with the new let-off motion and improved cotton picker, with no appreciable residual. Prorated over 20 years, this yields 0.3% per annum.

[40] Since the acquisition of this knowledge can also be considered as a human capital investment (in the form of foregone output), one might want to consider this kind of human capital as an input factor in a productivity calculation. Since I am not concerned here with purely exogenous technical change, that sort of calculation is not needed here.

[41] A 0.8% per annum wage increase for unskilled workers (David and Solar 1977) relative to more or less stable prices per loom (see above), combined with an elasticity of substitution of 0.15 and a capital factor share of 0.4, yields 0.05% per annum when prorated over 100 years.

[42] In particular, the weft fork reduced the penalty for delays in attending to broken weft and empty shuttle, reducing the level of skill needed to operate multiple looms efficiently.

growth for cotton textiles. For example, Nickless (1979) estimates quality-adjusted TFP growth of 1.1% per annum for the entire New England cotton textile industry from 1835-55, while I attribute labor productivity growth of 2.8% to technical change.[43] However, as I argue elsewhere (Bessen 2008), the TFP residual does not capture the contribution of technical bias to labor productivity growth. I include that contribution in my direct estimates here.

Conclusion

I find that technical change in weaving exhibited a strong labor-saving bias. It was neither Hicks neutral nor purely labor-augmenting. *Very little* of the capital deepening and labor productivity growth that took place in weaving can be attributed to factor substitution. That is, economic growth in weaving was hardly a story of "more machines."

On the other hand, it was not a simple story of "better machines," either. The growth in labor efficiency and in the capital-labor ratio were not entirely realized at the initial adoption of new inventions. Instead, this growth also involved significant learning on the job. Workers gained greater technical knowledge and/or skills that enabled them to handle more looms efficiently, realizing the potential benefit inherent in the new technologies. The story appears to be one of "better machines *and* better knowledge (human capital)." In this story, rising wages induced only a small substitution of capital for labor, but they also induced firms to invest much more in worker knowledge and skills, allowing more looms and more output per worker.

Too often, researchers view the part that technology plays in economic growth as limited to the role of inventions foisted on a mass of unskilled workers. I have argued elsewhere (Bessen 2003) that nineteenth century weavers were hardly unskilled, even though they were often uneducated, especially after the 1840s. Here I argue that the role of knowledge and skill acquisition among these workers was critical to technical change. This relationship between new inventions and new knowledge could be described as a dynamic version of "capital-skill complementarity." However, it is important to note that the skills developed here were not traditional skills nor was the human capital investment an investment in formal education.[44]

Although there has been speculation about the role of endogenous growth in the Industrial Revolution, researchers have so far found little supporting empirical evidence (see Crafts 1995). But

---

[43] I find a slightly higher TFP figure using my data. Looms per weaver grew at 3.1% per year and I use data from Layer (1951) to estimate the capital share of output at 42% in 1835 and 38% in 1855. This yields a rough (not quality adjusted) estimate of TFP growth of 1.7% per annum.

[44] As I found in my 2003 paper, the relationship between learning on the job and formal education is not simple.

most endogenous growth models only look at endogeneity in R&D and invention. My evidence shows substantial endogenous technical change in weaving, although not in invention per se, where the evidence is less clear. Moreover, my account highlights not only the endogenous influence of prices and wages, but also the changes in labor institutions and the labor supply that permitted deepening investment in on-the-job learning.

Of course, I have only investigated a single technology. Nevertheless, my engineering analysis makes clear that weaving technology had a lot in common with other mechanized technologies. Mechanization generally involves multiplying the number of machines that workers handle and, to the extent that these machines are imperfect or incompletely automated, the development of new technical knowledge and skills by workers is important. There is certainly evidence that other mechanized technologies involved learning on-the-job (see for example, Leunig 2003). As long as the implicit costs of that learning increase with the number of machines per worker, then other mechanized technologies should exhibit a similar endogenous response of the capital-labor ratio to prices and wages. Since much technological change during the nineteenth century involved mechanization, rising wages might have prompted a shift to more capital-intensive implementation of technology, possibly providing an explanation for the apparent persistent labor-saving bias then.

These considerations prompt another look at the role of technical change in nineteenth century economic growth. At first glance, economic growth during the nineteenth century in the US appears to be driven mainly by factor accumulation, not by technical change (Abramovitz and David 1973, 2001).[45] In part this is because estimates of the productivity residual during most of the century have been found to be relatively small. However, my findings suggest that what might appear to be accumulation-driven growth is, instead, driven by technical change, as Abramovitz and David point out. When technical change is strongly biased, the Solow residual fails to capture the complete role of technical change (Bessen 2008). Future research is needed to establish the relevance of these findings to other industries and technologies, including modern ones.

---

[45] Somewhat contrary to this view, Sokoloff (1984) finds substantial productivity growth even in manufacturing establishments that did not increase their capital, suggesting a possible role for learning.

Appendix

Efficiency gains in Table 1 are calculated using (1), (3) and the estimates in Table A2 applied to the benchmark mills in Table A1 as follows:

- Automatic let-off motion applied to Lawrence Company 1835, at 130 picks/minute and 48 picks/inch of weft (Montgomery 1840).
- Self-acting temple applied to Boston Manufacturing Company (BMC), at 70 picks/minute and 40 picks/inch of weft (Jeremy 1973).
- Weft fork applied to Boott Mills, assuming 150 picks/minute, 50 picks/inch and assuming 4 looms per weaver.
- Initial power loom assuming an increase to 70 picks/minute at 44 picks/inch (BMC) over 50 picks/minute on the handloom.
- Belt drive applied to BMC assuming an increase from 70 picks/minute to 130 picks/minute.
- Later power improvements taken as an increase from 130 picks/minute to 190 picks/minute (Young 1902).

Optimal looms per weaver

Assume that each worker stays employed for T periods and is paid a wage of w.[46] Then the mill's profit per loom can be obtained from (6) by integrating (ignoring discounting),

$$\pi = p\delta T - p\delta L(k) - \frac{w}{k}T, \qquad L(k) = \frac{k^{\alpha}}{\beta} \tag{8}$$

where p is the shadow price of weaving (exclusive of material costs, etc.). Differentiating with respect to k, yields a first order maximizing condition that specifies the optimal number of looms per weaver,

$$\ln \hat{k} = \frac{1}{1+\alpha} \ln \frac{wT\beta}{p\alpha\delta} \,. \tag{9}$$

---

[46] Of course, the weavers were actually paid on piece rate, but in equilibrium, piece rates would be adjusted so that weavers would earn the going wage for alternative employment. Also, I assume that T is sufficiently long so that learning is largely complete.

Table A1. Performance at Benchmark Mills

Mill (source)	Year	Yards / loom-hour	Looms/ weaver
Handloom hypothetical; 50 picks/minute at 80% utilization (Gilroy 1844, Marsden 1895, Draper 1907)	1810	1.5	1
Boston Manufacturing Company, Waltham (1820 Census of Manufactures	1819	2.1	*1.84*
Lawrence Company, Mill No. 2, Lowell (payroll records)	1835	3.9	1.84
″	1855	3.8	3.43
Boott Mills, Mill No. 1, Lowell (Burke 1876)*	1838	3.76	2.0
″ Note: in 1876 has weft fork & renovated power supply	1876	4.05	5.7
6 print cloth mills powered only by water (Wright 1880)	1879	3.73	5.08
5 print cloth mills powered only by steam (Wright 1880)	1879	4.13	6.0
3 mills producing coarse cloth (Young 1902)	1901	5.1	7.3
3 mills producing coarse cloth (U.S. Tariff Commission 1912)	1900-10	5.1	6.7

* Adjusted for 30 inch width using Draper (1907), page 170. Italics indicate estimate based on similar mill.

Table A2. Frequency and Duration of Loom Tasks

Tasks	Frequency	Duration (minutes)
Tasks performed while machine running		
Adjust warp tension	960 picks	0.15
Replace empty bobbin (Draper 1895)	960 picks	0.15
Tasks performed while machine stopped		
Fix smashes (assisted by helpers)	750000 picks	50
Adjust temples (Jeremy 1973)	6 inches	0.5
Back up loom (when replacing empty shuttle or fixing broken weft before weft fork)		4 seconds * no. looms * picks/minute/60
Replace empty shuttle (Draper 1895)	960 picks	0.2 + backup
Fix broken weft	3600 picks	0.2 + backup
Fix broken warp (Draper 1895)	6000 picks	1.0
Remove cloth, misc. (Draper 1903, Uttley 1905). Duration could be as much as 30 min./day (Draper), but often these tasks were performed by additional personnel.	108000 picks	10
Replace warp (Barlow 1878, Burke 1876, Draper 1907, Montgomery 1840, Young 1902). Duration could be as little as 15 min. (Young), but could also be several hours (Randall). Task might not involve weaver.	240 yds (1810-36) 320 yds (1838-80) 691 yds (1902)	60

Estimates without specific sources are based on interviews and measured times with Rick Randall at the Lowell National Historical Park and Mike Christian at the American Textile History Museum.

References

Abramovitz, Moses. 1993. “The Search for the Sources of Growth: Areas of Ignorance, Old and New,” Journal of Economic History, 53, No. 2, pp. 217-243.

Abramovitz, Moses, and Paul A. David. 1973. “Reinterpreting American Economic Growth: Parables and Realities,” American Economic Review, 63, pp. 428-37.

Abramovitz, Moses, and Paul A. David. 2001. “Two Centuries of American Macroeconomic Growth From Exploitation of Resource Abundance to Knowledge-Driven Development,” SIEPR Discussion Paper No. 01-05.

Acemoglu, Daron. 2003. “Labor- and Capital-Augmenting Technical Change,” Journal of the European Economic Association, 1, pp. 1–37.

Acemoglu, Daron. 2007. “Equilibrium Bias of Technology,” Econometrica, 75, No. 5, pp. 1371–1409.

Ahmad, Syed. 1966. “On the Theory of Induced Innovation,” Economic Journal, 76, pp. 344-357.

Antras, Pol. 2004. “Is the U.S. Aggregate Production Function Cobb-Douglas? New Estimates of the Elasticity of Substitution,” Contributions to Macroeconomics, v. 4, no. 1.

Asher, Ephraim. 1972. “Industrial Efficiency and Biased Technical Change in American and British Manufacturing: The Case of Textiles in the Nineteenth Century,” Journal of Economic History, 32, pp. 431-442.

Atack, Jeremy, Fred Bateman and Robert Margo. 2008. “Steam Power, Establishment Size, and Labor Productivity Growth in Nineteenth Century,” Explorations in Economic History, 45, pp. 185-198.

Atack, Jeremy, Fred Bateman, and Thomas Weiss. 1980. “The Regional Diffusion and Adoption of the Steam Engine in American Manufacturing,” Journal of Economic History, 40, pp. 281-308.

Barlow, Alfred. 1878. The History and Principles of Weaving by Hand and by Power. London: S. Low, Marston, Searle & Rivington.

Berndt, Ernst R. and Mohammed S. Khaled. 1979. “Parametric Productivity Measurement and Choice Among Flexible Functional Forms,” Journal of Political Economy, 87, pp. 1220-1245.

Berndt, Ernst, Charles Kolstad and Jong-Kun Lee. 1993. Measuring the Energy Efficiency and Productivity Impacts of Embodied Technical Change, Energy Journal, 14, pp. 33-55.

Berndt, Ernst R. and David O. Wood (1982). "The Specification and Measurement of Technical Change in US Manufacturing," Chapter 7 in John R. Moroney, ed., Advances in the Economics of Energy and Resources, Vol. 4, Greenwich, CT: JAI Press, pp. 199-221.

Bessen, James. 2003. “Technology and Learning by Factory Workers: The Stretch-Out at Lowell, 1842,” Journal of Economic History, 63, pp. 33-64.

Bessen, James. 2008. “Accounting for Productivity Growth When Technical Change is Biased,” working paper.

Binswanger, Hans P. 1974. “The Measurement of Technical Change Biases with Many Factors of Production,” American Economic Review, 64, pp. 964-976.

Blackorby, Charles, C. A. Knox Lovell and Marie C. Thursby. 1976. “Extended Hicks Neutral Technical Change,” Economic Journal, 86, pp. 845-852.

Bourne, John. 1865. Handbook of the Steam Engine, London: Longman, Green, Longman, Roberts and Green.

Brown, Murray and John S. De Cani. 1963. “Technological Change and the Distribution of Income,” International Economic Review, Vol. 4, No. 3 (Sep., 1963), pp. 289-309.

Burke, 1876. Transactions of the National Association of Cotton Manufacturers, No. 21, p. 8-9.

Chapman, Stanley and John Butt. 1988. “The Cotton Industry, 1775-1856,” in Feinstein, Charles H. and Sidney Pollard, eds., Studies in Capital Formation in the United Kingdom, 1750-1920,” Oxford: Clarendon Press.

Chenery, Hollis B. 1949. “Engineering Production Functions,” Quarterly Journal of Economics, 63, No. 4, pp. 507-531.

Clark, Gregory. 1987. “Why Isn't the Whole World Developed? Lessons from the Cotton Mills,” Journal of Economic History 47, pp. 141-173.

Clark, Gregory. 2007 *A Farewell to Alms*. Princeton: Princeton University Press.

Clarke, Richard N. and Lawrence Summers. 1980. “The Labour Scarcity Controversy Reconsidered,” *Economic Journal,* 90, pp. 129-139.

Copeland, Melvin T. 1912. The Cotton Manufacturing Industry of the United States, Cambridge: Harvard University.

Crafts, Nicholas. 1995. “Exogenous of Endogenous Growth? The Industrial Revolution Reconsidered,” Journal of Economic History 55, pp. 745-772.

Crafts, Nicholas. 2004. “Steam As A General Purpose Technology: A Growth Accounting Perspective,” Economic Journal, 114, pp. 338-51.

David, Paul. 1975. *Technical Choice, Innovation and Economic Growth*. Cambridge: Cambridge University Press.

David, Paul and Van de Klundert, Th. 1965. “Biased Efficiency Growth and Capital-Labor Substitution in the U.S., 1899–1960,” American Economic Review, 55, pp. 357–393.

David, Paul A. and Peter Solar, (1977). "A Bicentenary Contribution to the History of the Cost of Living in America," Pages 1-80 in Volume 2 of Research in Economic History , Greenwich: JAI Press, Inc.

Diamond, Peter, Daniel McFadden, and M. Rodriguez. 1978. "Measurement of the elasticity of factor substitution and bias of technical change," In: Fuss, Melvyn and Daniel MacFadden, (Eds.), Production Economics: A Dual Approach to Theory and Applications, vol. 2. Contribution to Economic Analysis, North Holland.

Draper, George Otis. 1895. "The Present Development of the Northrup Loom," Transactions of the National Association of Cotton Manufacturers, No. 59, p. 88.

Draper, George Otis. 1907. Labor Saving Looms, 3rd edition. Draper Corporation.

Draper, William F. 1903. "Continued Development of the Northrup Loom," Transactions of the National Association of Cotton Manufacturers, No. 74, p. 158.

Dublin, Thomas. 1993. *Women at Work: The Transformation of Work and Community in Lowell, Massachusetts, 1826-1860*, 2nd edition. New York: Columbia University Press.

Feller, Irwin. 1966. "The Draper Loom in New England Textiles, 1894-1914: A Study of Diffusion of an Innovation," Journal of Economic History, 26, pp. 320-347.

Fellner, William. 1961. "Two Propositions in the Theory of Induced Innovations," The Economic Journal, 71, pp. 305–308.

Ferguson, C. E. 1965. "Substitution, Technical Progress, and Returns to Scale," The American Economic Review, Vol. 55, No. 1/2 (Mar. 1, 1965), pp. 296-305 .

Fish, Charles H. 1896. "Test Showing Power Requirements to Drive Various Widths and Makes of Looms," Transactions of the National Association of Cotton Manufacturers, No. 60, pp. 179-80.

Fogel, Robert W. 1967. "The Specification Problem in Economic History," *Journal of Economic History*, 27, pp. 283-308.

Fox, Thomas William. 1894. *The Mechanism of Weaving*, London: Macmillan and Company.

Gibb, George. 1950. *The Saco-Lowell Shops: Textile machinery building in New England 1813-1949*. New York: Russell & Russell.

Gilroy, Clinton G. 1844. The Art of Weaving by Hand and by Power. New York: George D. Baldwin.

Habakkuk, H. J. 1962. *American and British Technology in the Nineteenth Century*, Cambridge, England: Cambridge University Press.

Harley, C. Knick. 1999. "Reassessing the Industrial Revolution: a Macro View," in Mokyr, Joel, ed., *The British Industrial Revolution: An Economic Perspective*, Boulder, CO: Westview Press.

Harriman, Henry I. 1900. "The Harriman Automatic Loom," Transactions of the National Association of Cotton Manufacturers, No. 68, p. 318.

Harvard Business School, Baker Library Historical Collections, Records of the Lawrence Company.

Hawkesworth, Alfred, 1896. “Looms and Loom Fixers; Weavers and Weaving Rooms,” Transactions of the National Association of Cotton Manufacturers, No. 61, p. 290.

Hayes, John L. 1879. American Textile Machinery, Cambridge: University Press.

Hicks, John. 1932. *The Theory of Wages*. London: Macmillan.

Jeremy, David J. 1973. “Innovation in American Textile Technology during the Early 19th Century,” Technology and Culture, 14, pp. 40-76.

Jeremy, David. 1990. *Technology and Power in the Early American Cotton Industry: James Montgomery, the Second Edition of His “Cotton Manufacture” and the Justitia Controversy about Relative Power Costs*, Diane Publishing.

Jones, Charles. 2005. “On the Shape of Production Functions and the Direction of Technical Change,” Quarterly Journal of Economics, 119, pp. 517-49.

Jorgenson, Dale W. and Barbara Fraumeni. 1981. “Relative Prices and Technical Change,” in Ernst R. Berndt and Barry C. Fields, eds., Modeling and Measuring Natural Resource Substitution, Cambridge, MA: MIT Press, pp. 17-47.

Josephson, Hannah. 1949. *Golden Threads; New England Mill Girls and Magnates*. New York: Russell & Russell.

Kalt, Joseph P. 1978. “Technological Change and Factor Substitution in the United States: 1929-1967,” International Economic Review, Vol. 19, No. 3 (Oct., 1978), pp. 761-775 .

Kennedy, Charles. 1964. “Induced Bias in Innovation and the Theory of Distribution,” Economic Journal, 74, pp. 541–547.

Kim, J. I. and Lau, L. J. 1994. “The sources of economic growth in the East Asian newly industrialized countries,” Journal of Japanese and International Economics, 8, pp. 235-71.

Klump, Rainer, Peter McAdam and Alpo Willman. 2007. “Factor Substitution And Factor-Augmenting Technical Progress In The United States: A Normalized Supply-Side System Approach,” The Review of Economics and Statistics, February 2007, 89(1): 183–192.

Landes, David. 1969. The Unbound Prometheus: Technological Change And Industrial Development In Western Europe From 1750 To The Present, London: Cambridge University Press.

Layer, Robert G. 1951. Papers, Baker Library Harvard Business School.

Lazonick, William and Brush, Thomas. 1985. “The 'Horndal Effect' in Early U. S. Manufacturing,” Explorations in Economic History 22, pp. 53-96.

Leunig, Tim. 2003. “Piece rates and learning: understanding work and production in the New England textile industry a century ago,” LSE Economic History Department Working Paper, 72.

Lyons, John S. 1987. “Powerloom Profitability and Steam Power Costs: Britain in the 1830s,” Explorations in Economic History, 24, pp. 392-408.

Macmillan’s Magazine. 1862. “Cotton Weaving and Lancashire Looms,” May-October 1862, v. 6, p. 451.

Margo, Robert A. 2000. *Wages & Labor Markets in the United States, 1820-1860.* Chicago: University of Chicago Press.

May, J. D. and M. Denny, “Factor-Augmenting Technical Progress and Productivity in U.S. Manufacturing,”International Economic Review, 20, pp. 759-774.

McCloskey, Donald. 1981. “The Industrial Revolution: A Survey,” in R. C. Flous and C. N. McCloskey, eds., *The Economic History of Britain Since 1700*, V. 1., Cambridge: Cambridge University Press.

McGouldrick, Paul F. 1968. *New England Textiles in the Nineteenth Century*, Cambridge: Harvard University Press.

Mohanty, Gail Fowler. 1989. “Putting up with Putting-Out: Power-Loom Diffusion and Outwork for Rhode Island Mills, 1821-1829,” Journal of the Early Republic, Vol. 9, No. 2, pp. 191-216.

Montgomery, James. 1840. *A Practical Detail of the Cotton Manufacture of the United States of America*, First Edition. Glasgow: John Niven.

Montgomery, James. 1843. *A Practical Detail of the Cotton Manufacture of the United States of America*, Second Edition. In Jeremy, David (1990) *Technology and Power in the Early American Cotton Industry: James Montgomery, the Second Edition of His “Cotton Manufacture” and the Justitia Controversy about Relative Power Costs*, Diane Publishing.

Moroney, John R. and John M. Trapani, 1981. “Alternative Models of Substitution and Technical Change in Natural Resource-Intensive Industries,” in Ernst R. Berndt and Barry C. Fields, eds., Modeling and Measuring Natural Resource Substitution, Cambridge, MA: MIT Press, pp. 48-69.

Nelson, Richard R. and Howard Pack. 1999, “The Asian Miracle and Modern Growth Theory,” Economic Journal, 109, pp. 416-436.

Nickless, Pamela J. 1979. “A New Look at Productivity in the New England Cotton Textile Industry, 1830-1860.” Journal of Economic History 39, pp. 889-907.

Nordhaus, William. 1973. “Some Skeptical Thoughts on the Theory of Induced Innovation,” Quarterly Journal of Economics, 87, pp. 208–219.

Nourse, Henry S. 1903. “Some Notes Upon the Genesis of the Power Loom in Worcester County,” Proceedings of the American Antiquarian Society, v. 16, October 1903.

Panik, Michael J. 1976. “Factor Learning and Biased Factor-Efficiency Growth in the United States, 1929-1966,” International Economic Review, Vol. 17, No. 3 (Oct., 1976), pp. 733-739 .

Pearl, D. J. and John L. Enos. 1975. “Engineering Production Functions and Technological Progress,” Journal of Industrial Economics, 24, No. 1, pp. 55-72.

Rodrik, Dani. 1997. “TFPG Controversies, Institutions, and Economic Performance in East Asia,” NBER Working Paper 5914.

Rothbarth, Edwin. (1946) “Causes of the Superior Efficiency of U.S.A. Industry as Compared to British Industry,” *Economic Journal*, 56, pp. 383-90.

Ruttan, Vernon W. 1997. “Induced Innovation, Evolutionary Theory and Path Dependence: Sources of Technical Change,” Economic Journal, 107, pp. 1520-9.

Salter, W. E. G. 1960. Productivity and technical change, Cambridge: Cambridge University Press.

Samuelson, Paul. 1965. “A Theory of Induced Innovations Along Kennedy-Weisacker Lines,” Review of Economics and Statistics, 47, pp. 444–464.

Sato,Ryuzo. 1970. “The Estimation of Biased Technical Progress and the Production Function,” International Economic Review, 11, pp. 179-208.

Shelton, Cynthia J., 1986. *The mills of Manayunk : industrialization and social conflict in the Philadelphia region, 1787-1837*, Baltimore: Johns Hopkins University Press.

Smith, Vernon L. 1957. “Engineering Data and Statistical Techniques in the Analysis of Production and Technological Change: Fuel Requirements of the Trucking Industry,” Econometrica, 25, No. 2, pp. 281-301.

Sokoloff, Kenneth. 1984. “Was the Transition from the Artisanal Shop to the Nonmechanized Factory Associated with Gains in Efficiency? Evidence from the U.S. Manufacturing Censuses of 1820 and 1850,” Explorations in Economic History, 21, pp. 351-382.

Solow, Robert M. 1957. “Technical Change and the Aggregate Production Function,” Review of Economics and Statistics, 39, pp. 312-320.

Strassmann, W. Paul. 1959. Risk and technological innovation, Ithaca, N. Y.: Cornell University Press.

Temin, Peter 1966a. “Steam and Waterpower in the Early Nineteenth Century,” *Journal of Economic History*, 26, pp. 187-205.

Temin, Peter. 1966b. “Labor Scarcity and the Problem of American Industrial Efficiency in the 1850's,” *Journal of Economic History*, 26, pp. 277-298.

Toevs, Alden L. 1980. “Input Substitution and Biased Technological Change in Resource-Intensive Manufacturing Industries,” in John R. Moroney, ed., Advances in the Economics of Energy and Resources, Vol. 3, Greenwich, CT: JAI Press, pp. 221-251.

U. S. Congress, House, United States Tariff Commission. 1912. Cotton Manufactures, 62d Cong., 1st session, House Doc. 643, p. 490-3.

U. S. Department of Commerce, Bureau of Foreign and Domestic Commerce, W. A. Graham Clark. 1908. “Cotton Textile Trade in the Turkish Empire, Greece and Italy,” Special Agent Series No. 18.

U. S. Department of Commerce, Bureau of Foreign and Domestic Commerce, W. A. Graham Clark. 1908. “Cotton Fabrics in Middle Europe, Germany,” Special Agent Series No. 24.

U. S. Department of Commerce, Bureau of Foreign and Domestic Commerce, W. A. Graham Clark. 1914. “Cotton Goods in Japan and their Competition on the Manchurian Market,” Special Agent Series No. 86.

U. S. Department of Commerce, Bureau of Foreign and Domestic Commerce, Ralph Odell. 1916. “Cotton Goods in China,” Special Agent Series No. 107.

Ure, Andrew. 1836. *The Cotton Manufacture of Great Britain*, London: Charles Knight.

Uttley, T. W. 1905. *Cotton Spinning and Manufacturing in the United States of America*, Manchester: University Press.

Walmsley, Herbert Edward. 1893. *Cotton Spinning and Weaving: A practical and theoretical treatise*, Manchester: Abel Heyward and Son.

Ware, Caroline. 1931. *The Early New England Cotton Manufacture*. Boston and New York: Houghton Mifflin.

Watson, John. 1863. *The Theory and Practice of the Art of Weaving by Hand and Power*. Glasgow: George Watson.

Wibe, Sőren. 1984. “Engineering Production Functions: A Survey,” Economica, 51, pp. 401-11.

Wilkinson, Maurice. 1968. “Factor Supply and the Direction of Technological Change,” The American Economic Review, Vol. 58, No. 1 (Mar., 1968), pp. 120-128.

Wills, John. 1979. “Technical Change in the U.S. Primary Metals Industry,” Journal of Econometrics, 10, pp. 85-98.

Wright, Carroll D. 1880. Report on the Factory System of the United States, Census of Manufactures, v. 2, pp. 52-4.

Young, Alwyn. 1995. “The tyranny of numbers: confronting the statistical realities of the East Asian growth experience,” Quarterly Journal of Economics, 110, pp. 641-80.

Young, Thomas M. 1902. The American Cotton Industry. New York: Charles Scribner’s Sons.

Yuhn, Ky-hyang. 1991. “Economic Growth, Technical Change Biases, and the Elasticity of Substitution: A Test of the De La Grandville Hypothesis,” The Review of Economics and Statistics, Vol. 73, No. 2, (May, 1991), pp. 340-346.

Table 1. Weaving Tasks and Inventions

Tasks	Invention	Date implemented in US	Increase in Loom Efficiency	Increase in Weaver Efficiency
Tasks performed while machine running				
Weaving (shed, pick, batten, let off warp, take up cloth)	Initial power loom	1814	41%	159%
Adjust warp tension	Automatic let-off adjustment	1835 + later		3%
Replace empty bobbin	Northrup loom	1895+		
Tasks performed while machine stopped				
Fix smashes	Protector (stops loom when shuttle not in the box, reducing frequency of smashes)	1814		
Adjust temples	Self-acting temple	1825	15%	23%
Replace empty shuttle	Weft fork (reduces time to back up loom)	1870s	7%	31%
Fix broken weft	″	1870s	2%	7%
Fix broken warp	Warp stop (not widely adopted for coarse work before 1900)	--		
Remove cloth, misc.	--			
Replace warp	Warp tying machine; larger beams	1904+		
Changes to machine speed				
	Belt drive & associated improvements	1828	55%	
	Steam power/water turbine, friction brake, shuttle guards, parallel picking motion	1870-1900	37%	
COMBINED			275%	359%

Table 2. Loom Productivity at Benchmark Mills

Mill			Yards / loom-hour	
			Estimates with $I = 0$	Actual
Boston Manufacturing Company	Waltham	1819	2.1	2.1
Lawrence Co., Mill No. 2	Lowell	1835	4.0	3.9
Boott Cotton Mills, Mill No. 1	Lowell	1838	4.1	4.1
Boott Cotton Mills, Mill No. 1	Lowell	1876	4.5	4.4
Water-powered mills* (Wright)		1879	3.8	3.7
New England mills (Young)		1902	5.1	5.1

*For this calculation, I assume that these mills, powered exclusively by water power, had not upgraded to use the weft fork.

Table 3. Capital Costs per Loom

	1836	1900	Notes
Handloom			
Cost of building/loom	$41.80		1
Cost of loom	$60.00		2
TOTAL	**$101.80**		
Powerloom			
Power capital per horsepower			
Waterwheel, gearing, etc.	$191.00		3
Waterwheel foundation	$45.00		3
Capitalized water rights (at 6% per year)	$200.00		3
SUBTOTAL, power capital/HP	$436.00		
Horsepower / loom	0.1195	0.1801	4
Power capital / loom	$52.10	$23.56	5
Building cost / loom (exc. of waterwheel foundation)	$41.80	$22.72	6
Cost of loom	$75.00	$41 – 58	7
TOTAL	**$168.89**	**$87 – 104**	

Notes: In nominal dollars.

1. See note 6.
2. Shelton (1986, p. 51) estimates the cost of handlooms in 1820 between $60 and $150.
3. Jeremy (1990, p. 253).
4. Bourne (1865) reports that a calico loom running 105 picks/minute in 1865 required about 0.1195 horsepower. Fish (1896) reports that at the end of the century, with looms running about about 160 picks/minute on similar cloth, looms required about 0.1801 horsepower.
5. The 1836 figure is $436 x 0.1195. The 1900 figure uses the larger figure for HP/loom but assumes that power costs/HP are 30% of their 1836 value.
6. Montgomery (1840) reports a four-story mill building with 80 HP cost $25,000. Deducting the cost of the waterwheel foundation, pro-rating ¼ (one floor) of the remaining cost to weaving, yields $41.80 for 128 looms. The 1900 figure comes from applying McGouldrick's (1968, pp. 240-1) mill building cost index for 1836 and 1886 to the 1836 estimate.
7. Montgomery (1840), Uttley (1905), and Young (1902, p. 9 and p. 15).

Table 4. CES Production Function Estimation

Monthly data for Lawrence Co. Mill No. 2, Upper Weave Room, 1834-55.

Dependent variable: ln *y*	Coefficients
σ	0.142 (0.069)
a	0.014 (0.031)
g	0.024 (0.003)
z	0.005 (0.004)
b	1.400 (0.052)
Number of observations	224
Adjusted *R*-squared	0.9154

Note: Non-linear least squares estimation; asymptotic standard errors in parentheses.

Table 5. Regressions on Individual Weaver Monthly Productivity

Dependent Variable: ln *y*	1		2		3	
α	-2.84	(0.07)	-2.83	(0.07)	-2.85	(0.07)
β	-0.71	(0.05)	-0.70	(0.05)	-0.75	(0.05)
Previous experience	80.60	(5.78)	79.97	(5.68)	86.10	(7.17)
Automatic let-off adjustment			0.03	(0.02)	0.01	(0.02)
New cotton picker			0.04	(0.02)	0.06	(0.02)
Gap in employment					0.06	(0.00)
Yankee					0.06	(0.01)
Literate					0.08	(0.01)
Cotton quality					-0.17	(0.05)
Year dummies	✓		✓		✓	
Month dummies			✓		✓	
Number of observations	14,315		14,315		14,315	
Adjusted *R*-squared	0.9837		0.9839		0.9843	
Residual growth per annum, 1835-55	0.01%		-0.17%		-0.02%	

Note: Non-linear least squares estimation; asymptotic standard errors in parentheses. Equation (6) is estimated using effective experience = days worked + γI[previous experience] where I is 1 if the worker had previous experience, 0 otherwise, and γ is an estimated parameter.

Table 6. Accounting for Labor Productivity Growth Per Annum in Coarse Cotton Weaving

	1835 - 55	1800 - 1900
Factor substitution	0.1%	0.1%
Technical change		
endogenous learning	2.5%	1.0 - 1.6%
inventions / other changes	0.3%	1.5 - 2.1%
Total labor productivity growth rate	2.9%	3.2%

Figure 1. Production function from simulations

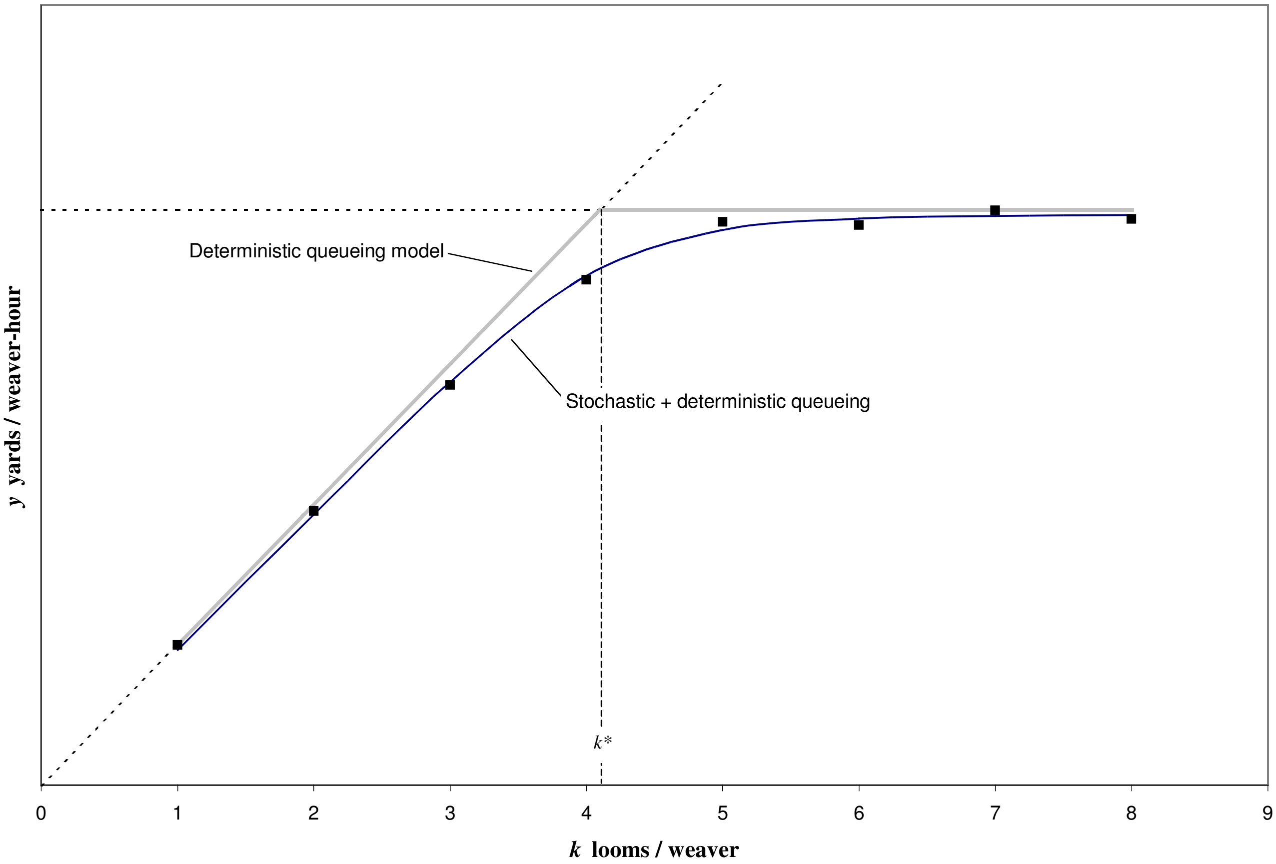
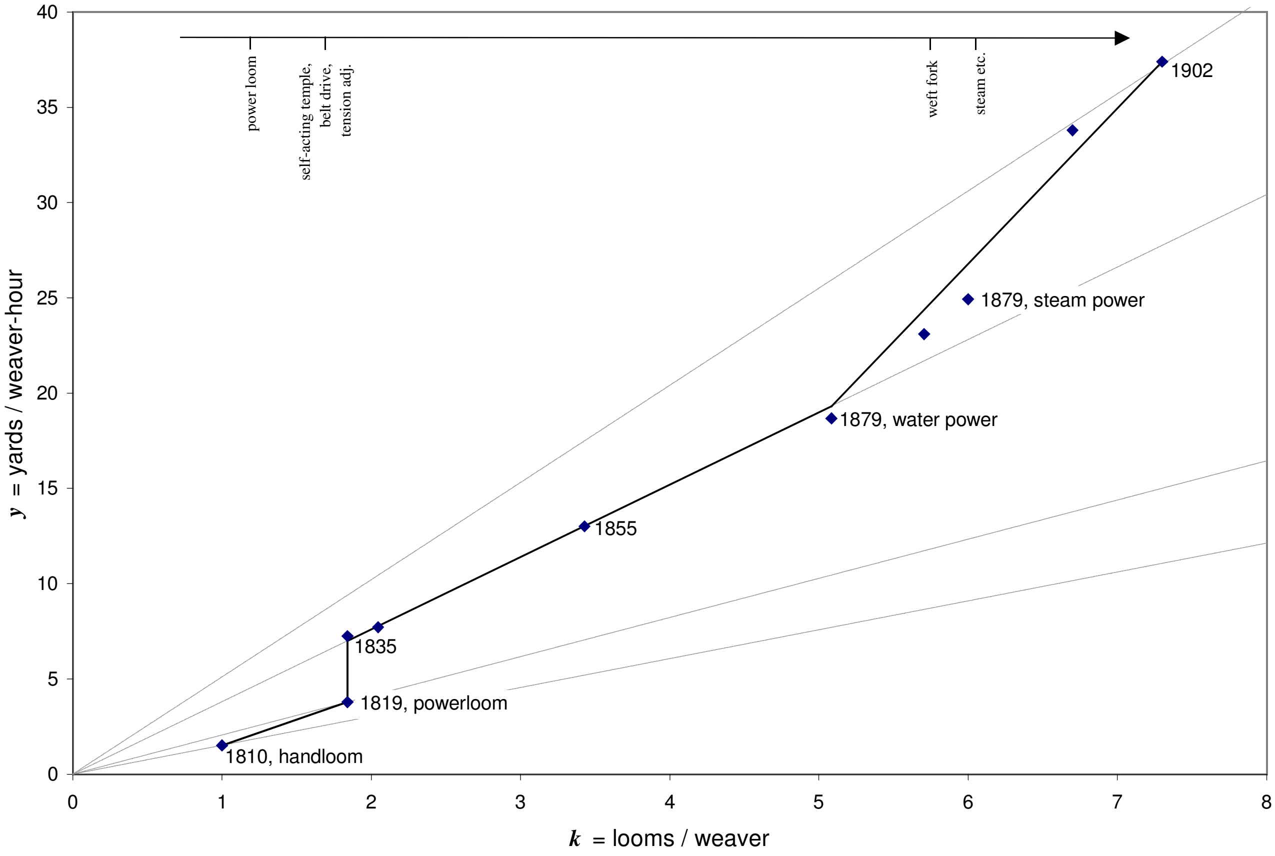


Figure 2. Realized Production at Benchmark Mills



Sources: See Table A1.

Figure 3. Capital Productivity at the 1842 “Stretch-Out”

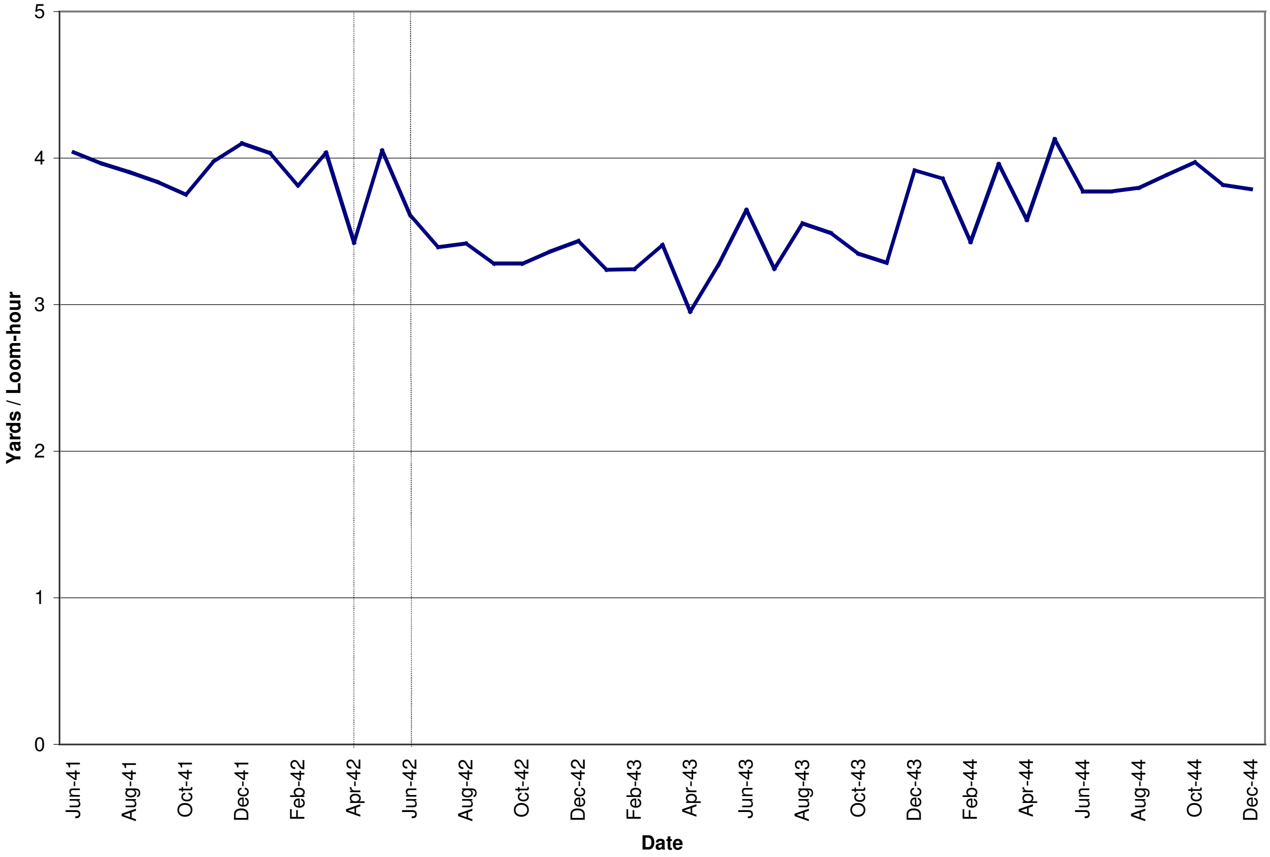
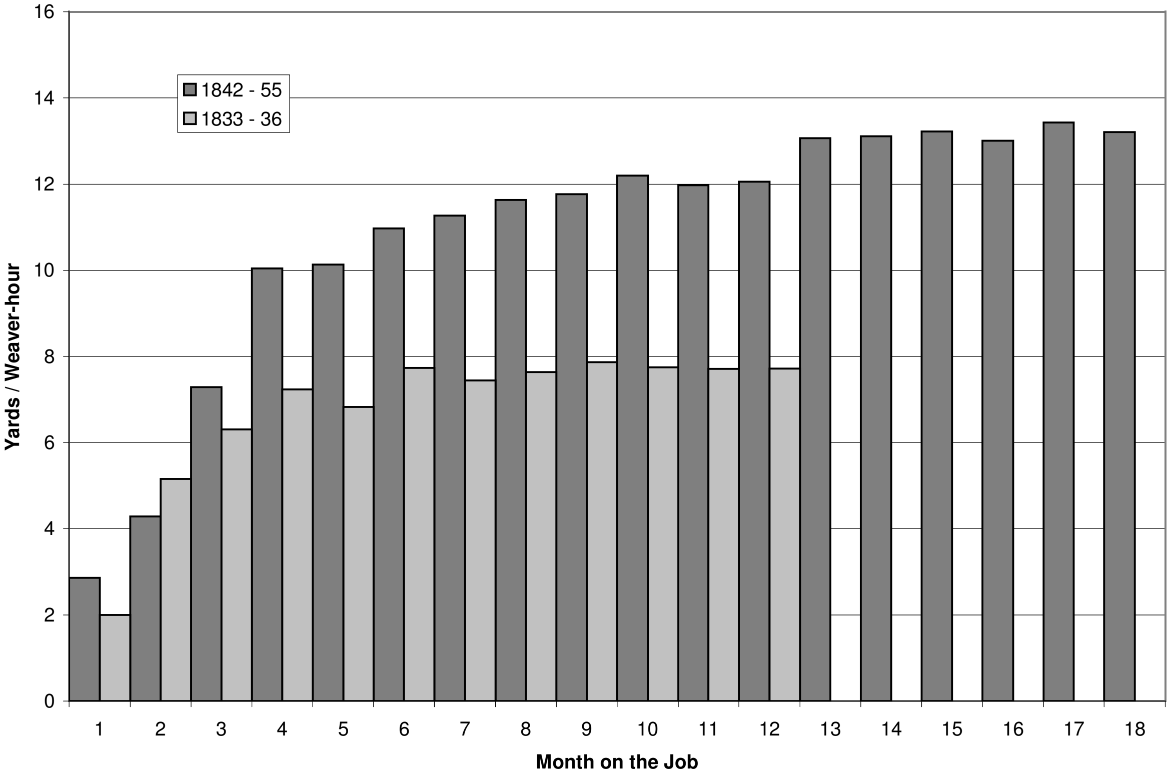
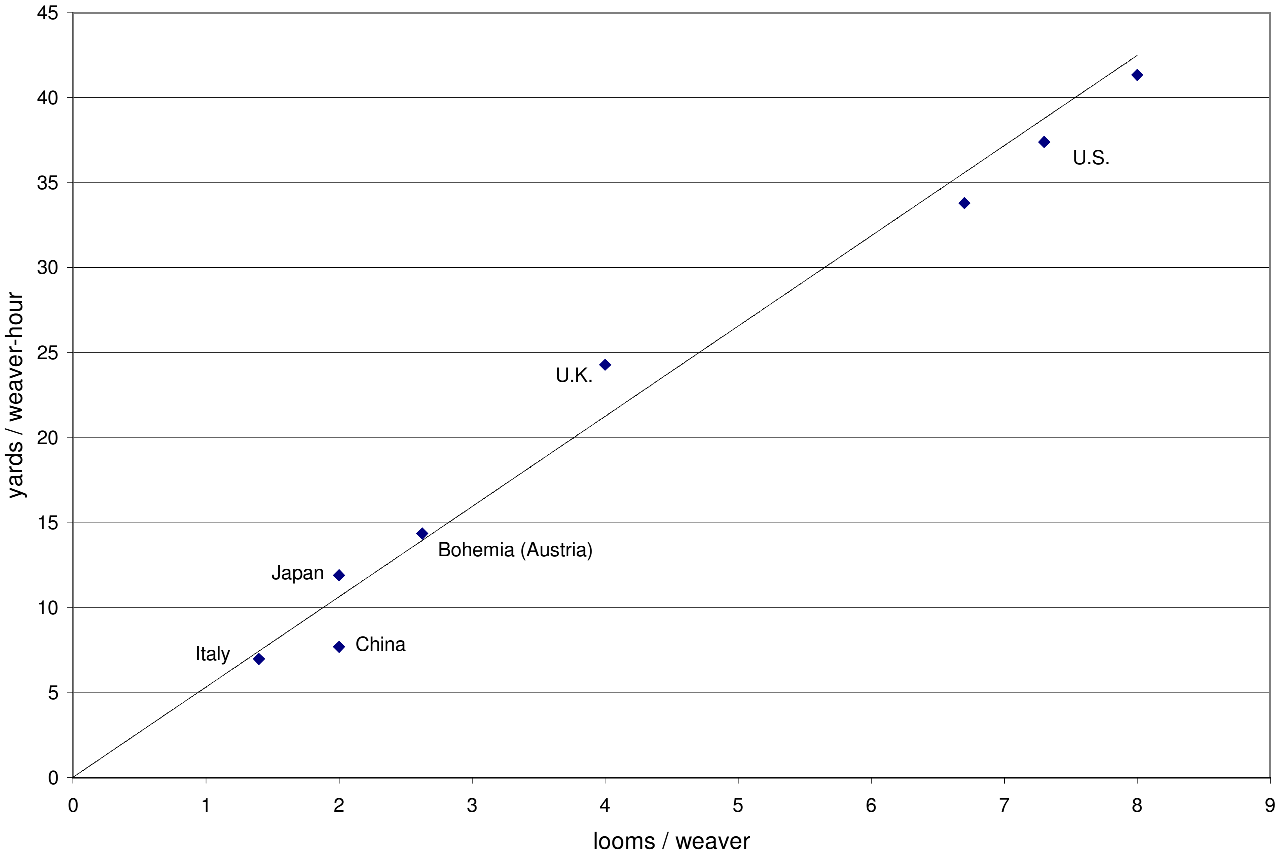


Figure 4. Learning Curves for Weavers in Lawrence Company, Mill No. 2, Upper Weave Room



Note: Means for balanced panel of 50 (1833-36) and 30 (1842-55) workers who entered the Upper Weaving Room, who worked for at least 12 (or 18) months in this Room. This sample excludes workers who spent no time on day rate (previously experienced) and workers who spend 72 days or more on day rate (permanent dayhands). In calculating yards per hour, workers on day rate were allocated the average productivity of all workers on day rate.

Figure 5. International Cotton Weaving Productivity, 1902-1910



Sources: US Department of Commerce, Bureau of Foreign and Domestic Commerce, Special Agent Series, No. 18, 24, 86, 107; U. S. Congress, House, United States Tariff Commission (1912); Young (1902).