10-1999

Waiting for Technology: Path Dependence as a Random Walk

James Bessen

Waiting for Technology:
Path dependence as a random walk

by James Bessen

WORKING PAPER

Original: 5/99

Version: 11/99

Abstract: The role of historical accident in technology selection has been difficult to measure. This paper develops a quantifiable model for a basic and widely applicable form of path dependence: the random walk. This real options model is applied to the transition in British cotton spinning at the beginning of the century.

In contrast to neoclassical models based on simple net present value calculations, when investment is irreversible, firms may choose to wait rather than to invest in a superior new technology. The magnitude and effect of this option to wait can be calculated. British spinning firms waited significantly before adopting superior technology, in line with the model. This failure to adopt (immediately) a superior technology can be described as “lock-in” as in the path dependence literature. But this lock-in need not be permanent.

Moreover, lock-in to an inferior technology does not generally imply any market failure or any benefit to intervention. Path dependence may, however, exacerbate existing market distortions.

JEL Codes: O3, O14, E22, N63

Keywords: Path dependence, technology adoption, technology diffusion, cotton spinning industry

Research on Innovation
6 Leslie Lane
Wallingford, PA 19086
jbessen@researchoninnovation.org
www.researchoninnovation.org

I. Introduction

The economic effect of the path dependence of technology has been difficult to quantify. Economic historians have little difficulty finding instances where seemingly trivial events weighed heavy on the subsequent course of technological development. For example, David [1985] presents the famous example of the QWERTY keyboard where design features of early typewriters dictated a keyboard layout that has been used long after those mechanical constraints disappeared. It has been argued that such phenomena might, under certain circumstances, generate inefficiencies and loss of social welfare. However, it has been difficult to assess whether these cases represent interesting but improbable theoretical anomalies, or whether they might not, in fact, be quite common and substantial.[1]

This paper builds a quantifiable model of path dependence based on a very simple and widely applicable assumption about the evolution of technology. Specifically, the profitability of technology is assumed to evolve as a random walk (with drift). This approach permits straightforward estimation of the economic effects of path dependence and rigorous analysis of the impact on social welfare. The model is applied to a well-known technology transition, the switch from mule spinning to ring spinning in the British cotton industry after the turn of the twentieth century.

This model simplifies the analysis of path dependence in two important ways. First, some of the path dependence models in the literature are based on marginal network externalities and unlimited increasing returns [e.g., Arthur, 1988, 1989]. However, such features are not inherent in the concept of path dependence and are often difficult to support empirically. Treating path dependence as a random walk permits the evaluation of economic effects independently of these additions. Positive feedback effects are treated as an extension to the basic model below.

Second, the assumption of the random walk provides a simple, consistent and plausible explanation of economic agents' knowledge and expectations. The importance of agents' expectations has been recognized in the path dependence literature, but Liebowitz and Margolis [1995] argue that much of this literature plays fast and loose with what agents actually know. For example, David suggests that the widespread acceptance of the QWERTY keyboard represents a failure of decentralized decision making, but Liebowitz and Margolis argue that David presents no

[1] The economics of QWERTY has of course been presented by David and challenged by Liebowitz and Margolis [1990]. But the question of whether such phenomena could have significant economic impact more generally remains unanswered.

evidence that centralized decision-makers had superior information that could have allowed a better decision early on.

The issue of agents' knowledge is, in fact, critical to the analysis of path dependence. Path dependence primarily poses a problem of *information* for the economic analysis of technologies. When technologies evolve randomly over time, the technology that will have the best expected net present value tomorrow does not necessarily have the best value today. That is, economic agents will have better information about technologies tomorrow than they have today. The path of technology evolution, buffeted by historical accident, reveals information.

Real options investment theory maintains that when historical accidents have persistent influence and investment is irreversible, then economic actors may rationally choose to wait rather than to invest. The option to wait has a positive value because waiting reveals better information. Economic actors might also realize a similar value to waiting before adopting a new, seemingly superior technology.

In contrast, the orthodox neoclassical model of technology choice is based on an assumption that economic agents have complete information about the future expected profitability of alternate technologies. Agents simply choose the technology that provides the greatest expected net present value. But when random events have persistent effect, then better information can be obtained by waiting and the neoclassical model is inadequate.

This paper analyzes technology adoption assuming that the profits generated by a technology evolve as a random walk (with drift) and that economic agents know the trend and variance of this process. The random walk is a mathematically simple form of path dependence where random current fluctuations generate permanent changes in future expectations.

The random walk is, of course, not the only assumption that could be made about agents' expectations. However, it is one of the simplest and weakest assumptions, it is widely applicable, and it is historically relevant—agents are known to evaluate informally the general trend and variance of profitability. Frequently, the profitability of technology is influenced by *many* technical, institutional, social and cultural factors, each difficult to predict. When these factors are independent and persistent, the random walk approximates the stochastic evolution of the profitability of technology. For similar reasons, unit root tests have shown a wide variety of economic time series to be consistent with a random walk [Greene, 1997, p. 851]. Moreover, there is frequently ample historical evidence, from trade associations and the like, that industry participants regularly evaluate the profitability of different technologies over time and hence possess, at least intuitively, some notion of the trend and variance of this evolution. The random walk is also useful as an assumption because it is amenable to the tools of real options theory. This permits quantification of the effects of uncertainty.

This basic model is a synthesis. On the one hand, random historical events have a sustained influence. Also, with irreversible investment, agents can be "locked-in" to a technology. On the other hand, agents act rationally given their limited information and this places limits on the purely random aspect of technology evolution. When the profitability of a neglected technology exceeds a threshold, new firms enter, breaking the "locks" on the old technology.

But this technology transition, if and when it occurs, is not the frictionless jump to a new production possibility frontier depicted in neoclassical models. The new technology will not, in general, enter the marketplace in a major way as soon as it is more profitable. Instead, faced with uncertainty about future profitability of the technology, firms may choose to wait. In particular, when a technology is expected to improve over time and when the firm's investment in technology is at least partially irreversible, then the option value of waiting may be significant. Expectations about future productivity growth and expectations about related price changes may substantially alter the decision to invest, even without previous sunk investment in the old technology. All else equal, there may be long delays in adopting new technologies, new technologies will tend to be substantially *more* profitable than the old before they are adopted, and firms may forego investment in old technologies even while these are still more profitable.

This model is applied to the familiar example of the adoption of ring spinning in the British cotton industry during the first decades of the twentieth century.[2] In contrast to their American and Japanese counterparts, the coarse section of the British cotton industry was "locked-in" to mule spinning technology. Nevertheless, as ring technology improved, the British industry began investing predominately in rings for new productive capacity. This transition was slow, however, and ring spinning only came to dominate equipment purchases in the coarse section many years after it first became more profitable. The model permits calculation of the contribution of path dependence to this delay; the industry behaved consistently with this model.

The role of technological expectations on a single, incrementally improving technology has been previously explored. Jeffrey Williamson [1968] and Brems [1968] examined the influence of technology expectations on equipment obsolescence and their model is nested within the model of

[2] An overview of the literature on this transition can be found in Payne [1990] and in Mass and Lazonick [1990].

technology switching developed here. Also, Kamien and Schwartz [1972] investigated the influence of discrete anticipated improvements (as opposed to the expectation of a stream of improvements) on investment.[3] Rosenberg [1976] cites several historical cases where technological expectations delayed adoption.

The slow adoption of new technologies has been widely observed and several explanations have been advanced for this delay. Much of the neoclassical literature on adoption has stressed the role of sunk costs in existing technology [Salter, 1966] or in complementary (inter-related) technologies [Frankel, 1955]. Note that the analysis developed here applies both to the replacement of existing technology and also to the adoption of technology for entirely new productive capacity. Even the latter may experience delays.

More recent models associate "diffusion lags" with the reduction of complementary costs such as specific human capital [Chari and Hopenhayn, 1990], learning-by-doing [Parente, 1994] and [Jovanovic and Lach, 1989], and search costs [Jovanovic and MacDonald, 1994]. Other explanations include strategic considerations [e.g., Dasgupta and Stiglitz, 1980] and political resistance [Mokyr, 1998].

All of these factors may pertain in some cases, but the model developed here applies even without complementary costs and in competitive markets free from political interference. That is, substantial adoption delays arise *endogenously* from path dependence and are consequently quite general. This means, moreover, that even without specific and dominant "positive feedback" effects, a technology may be "locked-in," that is, firms may exhibit substantial inertia and may be quite slow to adopt a superior technology.

Finally, at any point in time, this means that most firms in an industry may not be using the best technology. However, this does *not* mean that they—or a social planner—should necessarily do anything about that choice of technology. In general, if social planners have the same prior knowledge as private agents, they make the same technology choices in a model with competitive entry. When profitability follows a random walk and investments are irreversible, there may be considerable risk to choosing a new technology—risk faced by private agents and society alike. Only if the social planner somehow obtains superior information can one expect centralized decision-makers to choose the "right" technology.

[3] Their deterministic model has been extended to include stochastic and search elements by Jensen [1982], McCardle [1985] and Weiss [1994] among others.

Thus path dependence does not necessarily imply any remediable inefficiency even when inferior technologies are locked-in, as Liebowitz and Margolis argue [1995]. However, path dependence may still have a significant effect on social welfare. In particular, path dependence may exacerbate distortions and failures in *other* markets. For example, the failure of a market to provide re-training for cotton spinners may have substantially prolonged the transition to ring spinning and may have generated substantial welfare losses. Government intervention might have been appropriate, however, direct intervention over the choice of technology would hardly have been the most obvious and appropriate policy.

The next section describes the background to the problem and the assumptions made. In Section III a deterministic and a stochastic model are developed and the latter is applied to British cotton spinning in Section IV. Section V discusses welfare and efficiency considerations and Section VI concludes.

II. Background

The spinner's decision

During the first decade of the twentieth century, British cotton spinners continued to invest predominately in intermittent spinning technology (mule spinning) although continuous technology (ring spinning and, before that, throstles) was steadily gaining an advantage. These two technologies had competed for over a hundred years. Both technologies made dramatic advances in the late eighteenth century followed by years of incremental improvements. By the mid-nineteenth century, mule spinning had the advantage for all but the coarsest yarns and this technology dominated the British industry.

The rapid growth of the industry allowed several institutional changes that reinforced the advantage mules held. Mass and Lazonick [1990] detail these changes: a large pool of skilled mule spinners and equipment installers arose with specialized skills and with institutions for training more. The Liverpool cotton market grew to offer a wide range of cotton grades and staples and spinners developed specialized skills and equipment for producing mule yarn with a varying mix as supply conditions dictated. A worldwide marketing infrastructure grew up around the Manchester Royal Exchange. A financial market structure arose allowing a high degree of vertical specialization; very small, specialized spinning operations could receive financing to enter the market.

These factors are examples of the positive feedback effects such as learning-by-doing and network externalities discussed in some of the path dependence literature. All of these factors enhanced the relative profitability of mule spinning, tending to "lock-in" this technology especially in comparison to America.

However, this lock-in did not prove to be permanent or insurmountable. Incremental advances in ring spinning continued, many developed in America. The British textile machinery industry also introduced ring frames in 1872 and actively developed this new technology (largely for export trade), obtaining 408 patents on ring spindles between 1867 and 1892 [Farnie, 1990]. Meanwhile mule spinning technology stagnated, no longer making productivity advances at the close of the nineteenth century.

As ring spinning approached mule spinning in productivity (at different times for yarns of different fineness), the spinning entrepreneur faced a difficult decision. Rather than investing in equipment that could not be retrofitted and might only be resold at a loss, it might be better to delay until a better vintage of ring spinning technology came on the market. Rather than being locked into soon-to-be obsolete mule technology or a marginal early version of ring technology, it might be better to wait. The investment decision could not be based solely on static comparisons of current models; the entrepreneur also had to consider uncertain expectations about what improvements were likely in the near future.

Three distinct sources of uncertainty are involved in these expectations:

1. Future vintages of ring technology (and related technologies) may offer superior productivity.
2. Future increases in industry capacity may tend to limit profits. In particular, with free entry, new firms (or new capacity at old firms) can be expected to enter the industry if prices rise sufficiently. This entry threshold places an upper limit on product prices and hence on profits. And because new entrants can take advantage of the latest vintages of technology, this upper limit can be expected to decline over time.
3. Future profits depend on input and output prices and these are subject to random shocks. Because the technology is *embodied*, the technology adoption decision cannot be separated from the investment decision and so demand and supply conditions affect the calculation.

This situation is often described as "technological obsolescence" and firms have reckoned with this problem since the Industrial Revolution. Williamson [1968] provides evidence that

American ante bellum textile firms, faced with more rapid rates of technological change than their British counterparts, followed different replacement policies that led to more rapid scrapping of equipment.

To account for anticipated obsolescence managers have used ad hoc modifications to the present value rule. A common technique is to increase depreciation allowances. Thus, for example, Winterbottom [1907], in his manual for spinning managers, applies a depreciation rate of 4% in his pro forma calculations of cost and profitability for mule spinning. Yet the actual rate of retirement was under 2% [Saxonhouse and Wright, 1984a] and well-maintained mules were considered to suffer no loss of efficiency with age [Ryan, 1930].

Economists also use this ad hoc adjustment. For example, Sandberg, in his study of ring versus mule spinning [1974], applies a depreciation rate of 10% to spinning equipment to account for obsolescence. Sandberg also uses an ad hoc adjustment for capacity utilization in estimating hurdle rates for the adoption of ring spinning.

Although easy to calculate, such rules of thumb are ultimately unsatisfying. There are no clear guidelines for estimating such an enhanced depreciation rate—is it 4% above the interest rate, 10% above or something higher? Williamson [1968] and Brems [1968] provide a rationale for calculating an enhanced depreciation rate for a single, incrementally improving technology. However, their model does not address technology switching—where there is a choice between technologies as well as incremental improvement; nor does their model deal with uncertainty. But their model can be extended using real options methods to account for both technology transitions and uncertainty and this is what is done below.

This real options analysis indicates a substantially elevated hurdle rate during technological transitions; there is a large option value to waiting rather than investing. Although 4% or 10% depreciation rates accord with optimal calculations at times when there is no transition and only modest uncertainty, typical conditions during uncertain technology transitions imply temporarily much higher rates. Real options theory thus provides a better normative calculation of technology adoption than the neoclassical model with an obsolescence adjustment.

Of course managers in Britain's cotton industry did not use real options theory which employs sophisticated mathematics that had not yet been discovered. Nevertheless spinning managers did have to anticipate technology changes and respond based on their expectations. I argue that their behavior reflected the same expectations that are treated formally in real options theory and, although they may have used ad hoc decision rules, real options theory also appears to provide a first order approximation to their actual behavior.

Assumptions for a model of technology adoption

Model building entails specifying the prior knowledge (expectations) firms have about the three sources of uncertainty listed above. This paper makes the following assumptions. Machines embody a given state of technology and the vintage of machines created at time v has a fixed level of productivity. Productivity gains can be achieved by using a better vintage machine or perhaps by using machines of a different technology, but machines cannot be retrofitted with newer technology.[4] The new technology (ring spinning) is labeled A and the old technology (mule spinning) is labeled B. The old technology is assumed to be mature and thus does not improve over time.

Technology A does improve and these improvements are assumed to be Hicks-neutral. Also, assume that the machine-making industry is sufficiently competitive so that the benefits of productivity improvement are passed entirely to the industry using the machines. Set the initial price for the machine capacity required to produce a unit of output per year at 1 and set the initial variable cost of operating that machine capacity at c.

Managers are assumed to have observed prices, industry performance and technology trials and based on these observations to have formed the following expectations:

1. Both the equipment cost and operating cost necessary to produce a unit of output using technology A decrease at an expected rate μ for each new vintage. This technology improvement could be modeled as a stochastic (Poisson) process or as a deterministic process. Since these can be shown to generate the same results, the simpler, deterministic assumption is used here. For simplicity also assume that technology A uses the same factor proportions as technology B so that the ratio of operating costs to equipment costs is c for both technologies.
2. Firms are assumed to enter freely with no fixed costs other than the initial equipment costs. For simplicity of exposition, a "firm" is treated as owning a single machine so that existing firms adding to capacity can be treated as new firms entering.

[4] It was possible to retrofit throstles with ring spindles and this was done commonly in America during the 1870's [Mass, 1989], but mules could not be converted to ring frames and many of the incremental improvements to ring frames could not be implemented without replacing the frame.

3. Output prices, *p*, are assumed to follow a random walk with drift and firms know the trend and variance of this process. This is where path dependence enters. Thus shocks such as the constriction of markets by tariffs after World War I and the growth of Japanese competition are represented as random changes that permanently altered expectations. Of course input factors may also follow a random walk, but for simplicity of exposition just the product price variable is treated as a random walk (cotton costs will be considered when applying the model below).

Note that the random walk can encompass some of the positive feedback effects discussed in the path dependence literature. The random walk assumes a very specific sort of uncertainty, namely random events that have *persistent* effect. Weather and war are not likely to change long-term expectations permanently; the infrastructure growth and institutional change may. One class of phenomena that has persistent effect is positive feedback; e.g., a large pool of skilled mule spinners, facilitated by initial increasing returns to the size of the pool, is likely to persist because it represents a sunk investment. The random walk assumes that there are many independent “shocks” of this sort, some occurring in the future, and that economic agents have only a limited understanding of them (they know the cumulative trend and variance). In cotton spinning for example, a variety of different effects, some positive, some negative, acted to permanently shift the relative profitability of ring spinning: economies related to the growth of the Liverpool cotton exchange, the British textile equipment industry, the world-wide marketing infrastructure for coarse goods, the pool of skilled mule spinners, the emergence of tariffs in third world markets, the growth of the Japanese industry, and more.[5]

In contrast, the path dependence models of David [1985] and Arthur [1988, 1989] assume a single, dominant positive feedback effect that is fully known by economic agents. As discussed below, this requires significantly stronger assumptions about the knowledge of economic agents. Also, some of these models assume that network externalities exert a substantial *marginal* influence on profits. Initially, the model here assumes such externalities are *inframarginal*, that is, the increasing returns have been exhausted. For example, the externality of a pool of skilled mule spinners is treated as a random shock that occurred in the past, but any economies of scale in

---

[5] Some of these effects influenced costs rather than price. Also, note that positive feedback effects can generate both positive and negative shocks. For example, the manufacturers of cotton spinning equipment may have benefited from economies of scale as the British industry grew, allowing them to dominate world trade in cotton machinery, encouraging the growth of foreign competition that emerged as a negative shock to the British cotton industry.

training have since been exhausted. This affects the level of profits, but current increases in the pool of labor no longer affect the rate of profits. The objective here is to examine the effects of path dependence *per se* independent of additional complications, as this will be more widely applicable. Marginal externalities are discussed as an extension to the basic model below.

In addition, the following assumptions are made. A machine of vintage v maintains its productivity forever; that is, the flow of capital services does not depreciate and the machine does not fail. Machines may nevertheless be retired for reasons of technological obsolescence. This is a strong simplifying assumption, but adding stochastic retirements does not materially alter the results. Moreover, there is some evidence that retirements are driven substantially by obsolescence (Williamson [1968], Goolsbee [1998]).[6]

Also, investment is considered irreversible. There are at least two justifications for this assumption. First, new technologies frequently have large adoption costs. These are sunk costs that cannot be recovered on resale. Second, technological obsolescence guarantees that the resale value of a machine declines over time. In fact, resale prices are typically far below initial purchase prices especially for technology goods.

Finally, firms are considered to be risk neutral or, alternately, the Capital Asset Pricing Model is assumed to hold, allowing risk to be reallocated; in this case, the interest rate r reflects the influence of the firm's stock market beta.

III. A model of technology transition

Deterministic price expectations

First, consider a model where prices are not random. This model assumes that new firms, buying the latest technology, can freely enter the market. If the product price p is sufficiently attractive, firms will enter until the price decreases below the threshold at which new firms can profitably enter. Thus in this model price is determined endogenously by the entry condition.

Williamson [1968] considered the effect of deterministic price expectations on technological obsolescence. In this section a similar model is extended to include a technology

[6] Also, although it is frequently assumed that physical depreciation is independent of technological obsolescence, equipment is designed with useful economic life in mind. That is, the *designed* rate of physical depreciation is a function of the expected technological obsolescence. Thus, for example, personal computer keyboards tend to be designed for a much shorter life than electric typewriter keyboards or, for that matter, 1960's era computer terminal keyboards.

transition. Anticipating the inclusion of a stochastic price process, this model is based on Caballero and Pindyck's model of industry entry with aggregate uncertainty [Caballero and Pindyck, 1996, see also Dixit and Pindyck, 1994, chap. 8].

Firms will choose to enter at that product price where the cost of investing equals the value of being an active firm possessing the current best technology. The goal is to calculate this entry price threshold.

Let t represent time and set $t = 0$ to be that time when the costs of technology A just equal the costs of the older technology B. Consider first a prospective entrant at $t \geq 0$, buying vintage v of technology A ($v = t$). Let p be the product price (non-stochastic, temporarily), let $c \cdot e^{-\mu v}$ be the unit operating cost for this vintage of technology and let $e^{-\mu v}$ be the cost of equipment of this vintage sufficient to produce one unit output per annum.

Now firms that enter subsequently will have better technology and hence will be able to enter at lower thresholds, driving the price down. Eventually the current vintage will become obsolete. Let T represent the expected profitable life of the current vintage. The optimal value of T will be calculated as part of the solution to the problem.

Let $V(p, t)$ represent the value of an active firm with technology A of vintage v during the time interval $v \leq t \leq v + T$. This interval begins when vintage v is best practice and ends when vintage v becomes obsolete, so a firm would want to own vintage v only during this interval. The value of the firm must go to zero when its equipment becomes obsolete, so

(1) $$V(p, v+T) = 0.$$

While active, the firm will enjoy a profit flow of $p - c \cdot e^{-\mu v}$. Separating the value of the firm into flow and capital gain components,

$$V(p, t) = \left(p - c \cdot e^{-\mu v}\right) dt + \frac{1}{1 + r\ dt} \cdot E\left[V\left(p, t + dt\right)\right]$$

where $E\left[V\left(p, t+dt\right)\right] = V(p, t) + V_t(p, t)\ dt$, using subscripts to denote partial derivatives. Ignoring lower order terms such as $(dt)^2$ this yields

(2) $$V_t(p,t) - rV(p,t) + p - c \cdot e^{-\mu v} = 0 .$$

Equation (1) provides a boundary condition to this differential equation. Another boundary requirement arises from consideration of the free entry condition. At any time $t \geq 0$, entry will occur when the price is greater than or equal to threshold price $\bar{p}(t)$. Now it must be true that at this threshold the value of an active firm just equals the cost of entry, $e^{-\mu v}$, that is, $V(\bar{p}(t), t) = e^{-\mu t}$ since an entrant at time t will purchase equipment of vintage $v = t$. Thus the differential equation and boundary conditions are

$$\begin{aligned} &V_t(p,t) - rV(p,t) + p - c \cdot e^{-\mu v} = 0, \qquad v \le t \le v+T \\ &V(p, v+T) = 0, \qquad V(\bar{p}(t), t) = e^{-\mu t} \end{aligned} \quad . \tag{3}$$

This partial differential equation solves to (see Appendix)

$$\begin{aligned} &V(p,t) = \frac{p}{r+\mu} \cdot \left(1 - e^{-(r+\mu)(v+T-t)}\right) - \frac{c \cdot e^{-\mu v}}{r} \cdot \left(1 - e^{-r(v+T-t)}\right), \; v \le t \le v+T \\ &\bar{p}(t) = \bar{q} \cdot e^{-\mu t}, \qquad \bar{q} = \frac{r+\mu}{1-e^{-(r+\mu)T}} \cdot \left(1 + \frac{c}{r}\left(1 - e^{-rT}\right)\right) \end{aligned} \quad . \tag{4}$$

This solution is equivalent to Williamson's although derived differently.[7]

Although $\bar{p}(t)$ is defined as an entry threshold, in this perfect-foresight deterministic model the expected product price will equal this threshold value. By assumption, if price exceeds $\bar{p}(t)$, then an infinite supply of potential entrants will begin entering until price falls to the threshold. On the other hand, no firm would want to charge less than the entry threshold, and so this would also represent the market price.

Now T can be solved by the following consideration. In order for the entry threshold to be a rational expectations equilibrium, then at $t = v + T$ (when vintage v becomes obsolete) a firm with vintage v technology should make zero profits. Given that the product price is $\bar{p}(t)$, this means,

$$\bar{p}(v+T) = c \cdot e^{-\mu v} . \tag{5}$$

Given (4), this can be solved numerically for T.

It remains to find the entry threshold at $t < 0$, when technology B is still superior. Let $U(p,t)$ be the value of an active firm with technology B during this interval. Such a firm has operating costs c, so following the above logic, the differential equation for U is

$$U_t(p,t) - rU(p,t) + p - c = 0 .$$

Also, the cost of a new machine of technology B is 1, so at the entry threshold, $\bar{p}(t)$,

[7] Williamson uses a more straightforward present value calculation. The differential equation approach is used here because it can solve the stochastic problem considered below. It is possible to formally model the option value of the prospective entrant, however, this adds little to the analysis. See [Dixit and Pindyck, 1994, Chap. 8].

$$U\left(\bar{p}(t), t\right) = 1 .$$

Finally, at time $t = 0$, technology B is equivalent to vintage 0 of technology A in both equipment cost and operating cost. The values of firms with these two technologies must therefore be equal:

$$U\left(p, 0\right) = V\left(p, 0\right)\Big|_{v=0} .$$

The differential equation with boundary conditions is then

$$(6) \qquad U_t(p, t) - rU(p, t) + p - c = 0, \quad U(p, 0) = V(p, 0)\Big|_{v=0}, \quad U\left(\bar{p}(t), t\right) = 1$$

which solves to (see Appendix)

$$(7) \qquad \bar{p}(t) = (r + c)\cdot\left(1 - e^{rt}\right) + \bar{q}\cdot e^{rt} , \qquad t < 0 .$$

The combined price thresholds are shown over both domains in Figure 1A. Price is elevated before and after the transition point $t = 0$. Strictly speaking, however, the current model is somewhat unrealistic because output price is not stochastic here. As developed in the next section, however, this deterministic model can be viewed as a first approximation to a stochastic model. The stochastic model, in fact, has an entry price threshold qualitatively the same as in Figure 1. Given this, interpretation of the model is postponed to the stochastic version.

Stochastic prices

Following Caballero and Pindyck [1996] this model can incorporate a stochastic price process. The entry threshold $\bar{p}(t)$ becomes an upper reflecting barrier and below this, p follows a geometric Brownian motion with drift α and standard deviation σ:

$$dp = \alpha\ p\ dt + \sigma\, p\ dz$$

where dz is a Wiener process. Using Ito's Lemma,

$$E\left[V\left(p + dp, t + dt\right)\right] = V(p, t) + \alpha\ p\,V_p(p, t)\,dt + \tfrac{1}{2}\sigma^2 p^2 V_{pp}(p, t)\,dt + V_t(p, t)\,dt$$

so that the equivalent of (3) becomes

$$\tfrac{1}{2}\sigma^2\ p^2 V_{pp} + \alpha\, p V_p + V_t - rV + p - c\cdot e^{-\mu v} = 0,\ v \le t \le v + T$$

$$(8) \qquad \begin{array}{ll} (a)\ V(p, v + T) = 0, & (c)\ \lim_{p\to 0} V(p, t) \text{ bounded} \\ (b)\ V\left(\bar{p}(v), v\right) = e^{-\mu v}, & (d)\ V_p\left(\bar{p}(v), v\right) = 0 \end{array}$$

The third boundary condition (c) is in lieu of a more complicated exit threshold. The last boundary condition (d) arises because the entry price threshold must also be a reflecting boundary for the price process.[8] Note that conditions (b) and (d) hold when $t = v$.

This is a partial differential equation, but it can be solved analytically for the entry threshold (see Appendix) resulting in

$$\bar{p}(t) = \bar{q} \cdot e^{-\mu t}, \quad \bar{q} = \frac{r + \mu - \alpha}{1 - e^{-(r+\mu-\alpha)T} - e^{-\mu T} I(T)} \cdot \left(1 + \frac{c}{r}(1 - e^{-rT})\right), \qquad r + \mu > \alpha \tag{9}$$

where $I(T)$ is described in the Appendix. This solution reverts to the deterministic solution above when I equals 0. The value of T can be solved as above.[9] Tables 1 and 2 present results for a range of parameter values.

Using these values, the firm considering adopting technology A at $t \geq 0$ can apply a simple decision rule. If the product price is greater than $\bar{p}(t)$, then adopt; otherwise wait.

Characteristics of the solution

Figure 1A displays the change in the price threshold over time and the regions of adoption and inaction. The price threshold is a “reflecting boundary”—below this threshold, price evolves as a random walk; if price jumps above the threshold, new firms enter, adopting technology A or B depending on whether t is greater or less than zero respectively. The entry of the new firms continues until the price is driven back below the threshold.

Technology A is thus not automatically adopted as soon as it is the superior technology. Figure 1B displays several possible different paths starting from the same initial price at $t = 0$. Path A shows rapid adoption, path B shows somewhat slower adoption, and path C represents a case where the new technology is not adopted at all during the time period examined.

Any particular realization is random, and there is no definite waiting period before adopting the new technology. However, it is possible to calculate mean characteristics of behavior. First, one can calculate the extent of maximum price distortion. The increase in the threshold

---

[8] See Dixit [1993] or Cox and Miller [1965].

[9] The application of (5) is less clear than in the deterministic model because here there is a distribution of prices at any time. Also, a more realistic stochastic model would explicitly include an exit threshold for firms based on price. In lieu of this, firms with a given vintage of technology are assumed to stay in the market until they cannot make money at any price up to and including the entry threshold price; at this time their technology is obsolete. This assumption provides a condition for calculating T that is reasonably realistic as long as the market is expanding—in an expanding market, prices will tend to be distributed near the entry threshold. Note that a model that allowed exit at lower prices would have a lower value of T and hence a higher investment threshold.

around t = 0 represents the increased value of the option to wait, although this option has not been explicitly calculated. The extent of this price distortion can be measured by comparing the entry threshold at t = 0, $\overline{p}(0)=\overline{q}$, to the entry threshold that would exist if technology B were the only technology, p_0.[10] The percentage difference between these two numbers is also shown in Tables 1 and 2. As can be seen, the price distortions can be quite sizeable even for modest values of μ.

Second, one can determine the conditions under which technology A will be adopted with probability one. This is the "first passage" problem of random walks and the reader is referred to Cox and Miller [1965] or Dixit [1993]. The general result is

> Proposition. Lock-in. If $\mu+\alpha>\frac{1}{2}\sigma^2$, then technology A will be adopted with probability one; that is, the lock-in is only temporary. If this condition does not hold (and if $p<\overline{p}(0)$), then there is a finite probability that technology A will *never* be adopted even though it is superior. This is permanent lock-in.

Note that in this model when lock-in occurs, *neither* technology is purchased for new capacity. However, in a slightly more general model that allows for stochastic retirements of technology B, depending on the assumptions made, lock-in could be accompanied by ongoing purchases of technology B for replacement purposes, but no purchases of either technology for expansion of capacity.

Note also that lock-in can be permanent even when the productivity of technology A is growing. In this case, prices decline randomly at least as fast as the price threshold so that the threshold is never crossed.

Third, one can calculate the mean time to adoption of technology A, for the case where technology A is adopted with probability one. If the price at t = 0 is x, $x\leq\overline{p}(0)$, then the mean time to adoption of technology A is (see Appendix)

$$D(x)=\frac{1}{m+a-\frac{1}{2}s^2}\cdot\ln\left(\frac{\overline{p}(0)}{x}\right)\qquad\text{for}\qquad\mu+\alpha>\tfrac{1}{2}\sigma^2.$$

Clearly, the greater the initial price x, the shorter the time to adoption. Also, faster growth of productivity or of prices will hasten adoption and greater price uncertainty will delay adoption on average.

---

[10] $p_0=\beta\cdot(r-\alpha)(1+c/r)/(\beta-1)$ where β is the positive root of the fundamental quadratic for the differential equation, see [Dixit and Pindyck, 1994].

The price x will, of course, be historically determined. As a benchmark, the mean time can be calculated for $x = p_0$. These values are also listed in Tables 1 and 2. The wait periods are substantial. Combined with an additional period of no investment prior to time zero, a wait of a decade or so for first adoption of a superior technology would not seem unusual.

The time when technology B will be scrapped can also be determined. This is the same as the time when vintage 0 of technology A will be scrapped, namely $t = T$. As can be seen from Table 1, μ has a dramatic effect on equipment life as Williamson argued. The difference between T and D roughly corresponds to the "diffusion lag" since D marks when the new technology is first adopted and T is when it is widely adopted. As can be seen, diffusion lags of decades arise directly from the simple adoption decision even without complementary costs.

Tables 1 and 2 bracket a range of typical parameter values. Comparative statics may be summarized as

> Proposition. In an industry with free entry, with output price following a geometric Brownian motion, and with a technology transition that will occur with probability one (implying that $r + \mu > \alpha$ and $\mu + \alpha > \frac{1}{2}\sigma^2$), parameter changes (for typical parameter values) affect the timing of adoption of new technology as follows:
>
> 1. Increases in the rate of improvement in the new technology, μ, significantly postpone the mean time to first adoption of the new technology. Even very modest values of μ can generate significant lags. On the other hand, increases in μ also *decrease* the expected equipment life, and hence decrease the time until the old technology is replaced.
>
> 2. Increases in the interest rate substantially reduce the time to first adoption and modestly increase the equipment life and time to replacement.
>
> 3. Demand growth, represented by the exogenous upward drift in prices, α, also dramatically decreases time to first adoption and modestly decreases expected equipment life.
>
> 4. Greater uncertainty, represented by larger σ, tends to increase both time to first adoption and equipment life. Greater capital-intensity (smaller c relative to r) also increases equipment life.

These results provide some insights. Assuming small private firms are more liquidity-constrained (higher r), these small firms may first adopt new technology earlier than large firms with lower money costs. On the other hand, large liquid firms will tend to scrap old technology and replace it with new technology earlier than small firms. So technology adopters should exhibit a distinctive pattern over the product life cycle: the early adopters will tend to be small, the wholesale replacement of old technology will be led by large firms, and small firms may also hold on to the old technology longer.

Also, market segments that experience growing demand and less uncertainty will tend to adopt earlier and to replace earlier.

It is sometimes argued that low interest rates spur adoption of embodied technology by lowering user cost. The analysis here suggests the opposite. Lower interest rates do lower the user cost of new equipment but they also lower the cost of waiting. In a model with free entry, the latter effect dominates at least regarding first adoption of a new technology. Lower interest rates do reduce optimal equipment life, however.

Also note the important role played by the exogenous growth in demand. Demand growth has long been seen as a spur to technological change. Schmookler [1966] argued that demand growth provided an incentive to innovate. Salter [1969] argued for a vintage effect—that industries with growing demand build more new capacity and hence adopt relatively more equipment of recent vintage. The model here presents a different role for demand growth: growing demand hastens the first adoption of new technology.

Marginal feedback effects

As developed so far, this model has excluded the sort of feedback effects that have played a prominent role in some discussion of path dependence. It is important to note that the results achieved so far are thus independent of any such assumptions.

Positive feedback effects (beyond the localized or inframarginal effects that can be characterized as random shocks) can be incorporated directly into the model. This may incur a cost, however, requiring some strong assumptions that are difficult to support empirically and perhaps some loss of analytic tractability.

Consider, for example, the possibility that μ increases with the size of the installed base of technology A. There are, in fact, at least two reasons why the rate of productivity growth might depend on the rate of technology adoption, making it endogenous. First, incremental technology improvement often results from learning-by-doing (or learning-by-using), hence a faster rate of adoption may hasten the accumulation of experience resulting, in turn, in a faster rate of productivity growth. Second, it is usually assumed that innovators are motivated by pecuniary rewards. To the extent that incremental technology improvements result from the intentional activity of innovators, a faster expected rate of adoption implies a larger market for prospective innovations and hence a faster rate of productivity growth.

To incorporate this feedback effect, one needs to specify the functional form of $\mu(w)$ where w is the size of the installed base. Also, continuing the assumption that expectations are rational, one must assume that agents understand this relationship and correctly anticipate the growth of the installed base. This involves additional assumptions about how the installed base grows whenever price exceeds the threshold.[11] These required assumptions may seem rather strong and the existence of an analytic solution depends on the choice of $\mu(w)$ (numerical methods can be employed if analytic methods fail), however, positive feedback effects can be included.

As a practical matter, these assumptions may often be difficult to support empirically. For example, it seems quite reasonable to assume that in the early days of ring spinning the existence of an installed base was of some substantial importance to the pace of incremental improvement. But for the spinner of 1905 this externality may have been strictly inframarginal. It is difficult to argue that the size of the installed base still exerted a major influence on the rate of productivity change in 1905. Although widespread acceptance of ring spinning in the British cotton industry did not occur until well into the twentieth century, technological innovation by British textile equipment manufacturers in ring spinning was quite active from the 1870's. As noted above, 408 patents on ring spindles were issued in Britain between 1867 and 1892 [Farnie, 1990] and these manufacturers quickly dominated the world market for ring spinning machinery.[12] Although ring spinning was not widely accepted in Britain during this time, a minority did accept it. And the British cotton industry was so large that this relative minority was an absolutely large number (over 6 million ring spindles by 1907 [Copeland, 1909]) and Britain had the second largest installed base of ring spindles (after the United States) until 1936 [Farnie]. This base was apparently large enough to provide adequate learning-by-doing and, with the additional incentive of export trade, to spur innovation. Moreover, there is little evidence that the rate of productivity change increased substantially once rings were more widely accepted.

Such positive feedback effects may be an important aspect of technological change. However, given the difficulties they impose on a quantifiable model and the difficulties of empirical

[11] Given that economists have not been particularly successful building models to predict investment, it may seem to be a rather strong assumption that private agents had such knowledge in 1905.

[12] Although American patents are not necessarily equivalent to British patents, by comparison, 373 patents on ring spinning were issued between 1870 and 1903 in America where ring spinning dominated [Draper, in Copeland 1909].

support, I proceed using a simpler model of basic path dependence that does not include these marginal feedback effects.

IV. Ring spinning versus mule spinning

Estimating the parameters

The usefulness of the options approach is illustrated by calculations made for a hypothetical cotton spinner circa 1905. It is not difficult to calculate the relevant parameters for a prospective British spinner of 32s warp yarn to apply the model for an industry with free entry.[13] This industry was manifestly one with few barriers to entry and easy financing readily available even for small firms [Lazonick, 1983]. There were large numbers of spinning firms and large numbers of new entrants in boom years such as 1907. Thus the industry conditions corresponded with the free entry assumptions of the model. Also, firm financial assets were actively traded so risk could be shifted.

To apply the model and calculate a price threshold, it is necessary to estimate five parameters: the trend and variance of the price process, α and σ^2, the discount rate, *r*, the operating costs (relative to investment costs), *c*, and the incremental rate of productivity improvement for the new technology, μ. The operating costs facing a mule spinner of this era can be obtained from Winterbottom [1907, p. 231] and are shown in Table 3. [14] Lazonick [1981] provides adjustments to this to calculate the costs for ring spinning for warp yarn or yarn produced in an integrated spinning and weaving mill (weft yarn produced in a vertically specialized mill would have faced some additional transportation or rewinding costs). The figures presented here are *pro forma* estimates; any actual spinner would have faced a significant range of variation in these costs.

The relevant price series is the "margin" for 32s yarn—the difference between the price of the yarn per pound and the cost of American middling cotton with an adjustment for waste.[15]

---

[13] 32s yarn designates a relatively coarse yarn of 32 hanks (1 hank is 840 yards) to the pound. The calculations are performed for the manufacture of warp yarn; weft yarn had additional transportation or winding costs [Lazonick, 1981]. This calculation also applies to the production of weft yarn in an integrated spinning and weaving mill.

[14] Winterbottom used a depreciation rate of 4% as noted above. This has been replaced with a depreciation rate of 2% that is closer to the actual retirement rate.

[15] Following Winterbottom [1907, p. 232] waste is assumed to be 10% but the value of waste cotton can be recaptured at a value of 2.5% of the value of the cotton used. The price series comes from Robson [1957]. The margin

Recall that the model assumes that this price follows a geometric Brownian motion below the threshold. That is, below the threshold

$$dp = \alpha\, p\, dt + \sigma\, p\, dz \qquad \text{or using Ito's lemma,} \qquad d \ln p = \left(\alpha - \tfrac{1}{2}\sigma^2\right)dt + \sigma\, dz$$

or $$\ln p_t = \ln p_{t-1} + \left(\alpha - \tfrac{1}{2}\sigma^2\right) + \varepsilon_t, \qquad \varepsilon_t \sim N\left(0, \sigma^2\right).$$

That is, the logarithm of *p* is an $I(1)$ process. Augmented Dickey-Fuller tests on log *p* from 1883 to 1910 fail to reject the hypothesis of a unit root, implying that the assumption of geometric Brownian motion cannot be rejected.

This suggests that the mean and variance of the first differences of log p might be used to estimate the trend and variance. However, *p* follows a *regulated* process—variations of *p* above the price threshold are reduced to the threshold by the addition of new capacity, hence the observed price series may be censored. For the estimate of variance, this censoring implies that the variance of the first differences will tend to understate the true variance somewhat. The variance of the first differences of log margin from 1884 to 1910 is .032 . As a rough adjustment, since investment episodes do happen fairly frequently, use an estimate that is 10% greater, $\hat{\sigma}^2 = .035$.

Any long run increases in price, however, are offset by additions to capacity. Assuming constant returns to scale in capacity, the long run trend growth in price below the threshold should equal the estimated growth in price *plus* the estimated growth rate in capacity. Using first differences, the mean growth rate of prices is .000; the growth rate in cotton consumption (as a long run measure of capacity growth) is .009 . Therefore $.000 + .009 = \hat{\alpha} - \tfrac{1}{2}\hat{\sigma}^2$, yielding $\hat{\alpha} = .0265$.

The interest rate typically applied to spinning firms was 5% by historical accounts, hence $r = .05$.[16] From Table 3, annual capital costs per pound of ring warp yarn were .27d, excluding depreciation, so the cost of capital purchased was .27d / .05 = 5.40d. All other costs totaled 1.22d, so taking the cost of capital as numeraire, c = 1.22d / 5.40d = .226.

---

used is for standard grades of cotton and yarn. Actual manufacturers used varying grades of cotton, often mixing different grades and staples, and producing different qualities of yarn ad different prices. Nevertheless, this particular benchmark is roughly illustrative of the price margins a prospective manufacturer would have used in making an entry decision. At least one comparison of this benchmark to actual achieved margins is resonably close [Daniels and Jewkes, 1928].

[16] The model assumes that the Capital Asset Pricing Model applies to the firm's value and this means that *r* should reflect a risk component in addition to the risk free interest rate. Implicitly this is assumed to be small.

It remains to estimate productivity growth. First, the model assumes that the old technology is stagnant and, as it turns out, mule spinning had at best negligible productivity growth from 1885 to 1910.[17] On the other hand, ring spinning had been steadily improving since key technical advances in the 1860's allowed spindle speeds of 5,500 rotations per minute. By 1875 this increased to 7,500 r.p.m. and 10,000 r.p.m. some years later [Copeland, 1909,1912]. From the 1880's to 1909 further incremental improvements were made in the stability and energy efficiency of the machine. Fewer yarn breaks allowed a doubling in the number of spindles per worker, relatively less fuel consumption, greater output and better quality. These improvements translate into a rough rate of sustained productivity growth (μ) of about 2% per annum.[18] Moreover, an expectation of 2% productivity growth would not have been far off the mark. The next two decades brought a number of notable improvements in the preparation of yarn [Saxonhouse and Wright, 1984] and in complementary processes [Lazonick and Mass, 1984] that improved productivity of spinning especially in integrated weaving and spinning firms.

Applying the model

To summarize, the estimates of the relevant parameters are: $\alpha = .0265$, $\sigma^2 = .035$, $r = .05$, $c = .226$, and $\mu = .02$. These parameters applied to the values in Table 3 yield the following results. The price threshold at $t = 0$, $\overline{q}$, is .52 times the cost of capital. At the point of cost parity between mule and ring warp spinning, the entry threshold was a cotton margin (after deducting for waste and a 3.5% selling expense/discount taken off the sale price) of 5.40d * .52 = 2.81d per pound. This was 25% higher than the entry threshold that would have applied had there been only mule spinning. The mean time to first purchase of ring equipment after this parity point (given a price of p_0 at that time) was 7.7 years. The expected equipment life was 42 years, roughly equivalent to the value implied by Saxonhouse and Wright's estimate of the scrapping rate.

---

[17] Jones [1933] originally estimated a rate of 0.16% per annum multi-factor productivity growth over this period. Sandberg [1974, p.108] reworking his figures, finds a multi-factor productivity gain of 0.38% per annum. However, his calculation includes a quality adjustment that was not captured by the firm and so is not relevant for our purposes. Removing this eliminates most of the productivity growth. Lazonick and Mass actually find declining labor productivity from 1900 to 1913 [1984].

[18] The increases in spindle speed generate direct productivity increases at about this rate. Assuming a halving of labor, fuel and miscellaneous supply costs between 1885 and 1905 and a 50% cost share for these items, also yields about a 2% per annum gain.

The investment behavior of our hypothetical spinner is quite sensitive to the exact timing of parity between the two processes. Figure 2 shows the actual cotton margins and the calculated entry thresholds assuming parity was achieved 1.) in 1904 and 2.) in 1908. If parity had been achieved in 1904 (or 1905 for that matter), our spinner would have purchased rings in 1906 and again in 1912 and 1914. But if parity had not been achieved until 1908, our spinner would have purchased mules in 1906 and might not have purchased rings until the end of the next decade.[19] Note that if there had been no ring technology, the purchase threshold for mules would have remained at p_0 (2.25 d/lb.), and mules would have been purchased in 1904-6, 1911-12, and 1914. Thus the transition to the new technology would have decreased the frequency of investment overall.

Slight differences in cost can clearly generate large differences in the timing of adoption. And, of course, there was a rather broad dispersion of costs for different yarn counts, warp versus weft, specialized versus vertically integrated production, and other factors including differing expectations. This means that some spinners would have achieved parity earlier than others, hence some portion would have followed a pattern similar to the 1904-parity threshold and another portion would have followed a pattern similar to the 1908-parity threshold. These purchases would have been for new capacity and as suggested this activity would have been concentrated in selected boom years. In addition, a certain share of spindle orders would have been purchased to replace failed or deteriorated units. In cases where only a small portion of a firm's total spindleage needed to be replaced, firms would most likely purchase the same type of equipment they already had. These maintenance replacement purchases would have been fairly constant (except for the war years) and larger for mules than for rings.[20]

The actual pattern of equipment purchases in the coarse section of the industry roughly conforms to this picture. Figure 3 displays estimated orders from six large British textile equipment manufacturers intended for sub-40s production.[21] Major purchases of mules took place in 1905-7 and 1911-12 and major purchases of rings took place in 1905-7, 1912-13, and 1919-20. Note,

[19] The chart only displays to 1915 because World War I constrained production, disrupted markets and introduced a sharp inflation. Note that the prices in this chart have been shifted one year earlier to correspond more closely with the series of equipment purchases. Since prices are largely set after the harvest in the Fall, the following year's average prices will reflect the anticipated demand that motivates purchases of equipment.

[20] A more complete model would, of course, formally consider this form of replacement but at the expense of some complication.

[21] These data are derived from Saxonhouse and Wright [1984a,b] and supplemental data supplied graciously by Gary Saxonhouse. Calculations are available from the author.

however, that mules were predominately purchased during the first two booms and not until the boom of 1919-20 did rings predominate. This delayed dominance of rings is confirmed in Figure 4 which displays a moving average of purchases. Not until the latter part of the second decade did rings dominate new equipment purchases. Thus it appears that the majority of the coarse section of the industry followed the pattern of “1908 parity” shown in Figure 2 and a minority followed the pattern of “1904 parity.”

This accords well with Lazonick’s cost estimates. As in Table 3, ring spindles purchased for warp yarn and for use in integrated mills would have, on average, achieved parity sometime before 1905, but allowing for some variance in costs, a portion of these would not have achieved parity until later. In total this group probably represented over half the spindles in coarse spinning, so somewhat less than half of the firms (weighted by their demand for spindles) would have achieved parity before 1905.[22] Assuming a 2% per annum productivity growth in rings, the remainder would most likely have achieved parity shortly thereafter and producers of weft yarn might have achieved parity around 1910 or so.[23] So the actual purchasing pattern for the coarse section of the industry is consistent with these calculations.

In any case, the performance is at odds with the simple neoclassical model—the actual adoption of rings appears to have occurred with some significant delay after rings achieved superiority. Rings dominated new purchases only after 1915, but cost calculations indicate that parity was achieved for most of the coarse section well before this. In addition, Saxonhouse and Wright [1987] report that rings accounted for only 38% of the spindles purchased for warp yarn between 1901 and 1914, even though rings would have been superior for this group quite early during this interval. It is possible, of course, that this delay could have been the result of simple conservatism or “entrepreneurial failure”. But the nature and magnitude of the delay are entirely consistent with a model that incorporates uncertain path dependence.

As noted above, a modified version of the simple neoclassical model, using an obsolescence enhanced “depreciation” rate, also inadequately describes technology transitions. It is

---

[22] About a quarter of all spindles were employed in integrated mills at this time (35% in 1878 declining to 23% in 1911 [Robson, 1957, p. 120]). But these were predominately producing coarse yarn, so nearly half of all coarse spindles were probably employed in integrated spinning and weaving mills. In addition, a substantial portion of the remaining specialized producers would have been making warp yarn.

[23] There has been some controversy over exactly how much additional cost weft producers incurred (see Lazonick [1987] and Saxonhouse and Wright [1987]. See Robson [1957] for background). Nevertheless, taking Lazonick’s lower estimate for the cost of rewinding, parity would have been achieved for weft production about 5 years after parity was achieved for warp production. Even making a larger cost allowance for rewinding, parity for weft production would still have occurred before 1915, that is, before rings came to dominate spindle purchases.

instructive to calculate the hurdle rates and the obsolescence-related "depreciation" implied by the calculated thresholds. The return on capital necessary to generate a price threshold of 2.81d/lb. is 29% .[24] This hurdle rate includes the effects of uncertainty and obsolescence. By comparison, the return on capital investment in mules necessary to generate a price threshold of p_0 is only 17%. This latter hurdle exceeds the 5% interest rate only because of the effects of uncertainty. Nevertheless, there is no clear relationship between the difference between these hurdle rates and expected equipment life, 42 years. Any effort to infer a depreciation rate from observed equipment lives is not well founded. Moreover assumed depreciation rates of around 10% are likely to fall far short of the appropriate hurdle rate indicated by the real options model.

V. Welfare and efficiency

The path not taken

As elaborated above, path dependence implies that private agents in a competitive market do not necessarily use the best technology at all times. Private agents may choose a technology that is momentarily better, but which is later superceded by another technology. Given the inertia resulting from uncertainty and irreversibility (and possibly reinforced by other changes in the economy), private agents do not necessarily purchase the superior technology as soon as it is available, and they may, in fact, never purchase it.

It is sometimes argued that such a situation represents a market failure and this is taken as evidence that centralized selection of technologies is superior to decentralized choice of technology. But such an inference is incorrect. Path dependence by itself does not imply any market failure. In fact the following can be shown:

> Proposition. If the above model holds and if a social planner has the same information as private agents, then the social planner will follow the same policy as private agents.

This proposition is an instance of a more general argument described in Dixit and Pindyck [Chapter 9, 1994] and I refer the reader there for details. Intuitively, society faces the same risks implied by path dependence as do private agents. Society's option to delay purchasing a newly superior technology is the same as that of private agents, so the social planner will follow the same policy.

---

[24] That is, operating costs excluding capital costs are 1.22d/lb. so gross profits are 2.81 – 1.22 = 1.59d/lb. per 5.40d capital.

The virtue of the formal model presented here is that it makes explicit both the prior knowledge of private agents and social planners and that it quantifies the effect of uncertainty arising from path dependence. This provides a more rigorous framework for evaluating possible market failure and recourse to government policy related to path dependence.

For example, consider again the transition to ring spinning in the coarse section of the British cotton industry. During the 1920's Britain's export market for coarse cotton goods fell sharply as many nations imposed tariffs and as Japanese exporters captured substantial market share in Asian markets. Lazonick and Mass [1983] have argued that had this industry integrated spinning and weaving operations to a greater degree and employed ring spinning to a greater degree during the decade or so before World War I, then it would have been more efficient and would have better weathered this shock.

Assuming that this is true, and taking their suggestion a step further, one can ask whether Britain would have benefited from government intervention to promote vertical integration and the adoption of ring spinning. First, note that the choice of organization (vertical integration) can be considered part of the technology choice although this implies additional costs (e.g., manager's salaries), additional investment (e.g., organizational learning), and perhaps additional risks (e.g., the risk of hiring poor managers). Hence the model is applicable.

But direct government intervention in the choice of technology would seem to require that the government had better information about the future than did private agents. If the government also believed in 1905 that demand would increase on average at 2.65% per annum (α), then there would not be any reason for direct intervention. And if the government knew otherwise, then why would not firms also know otherwise?

Moreover, the model indicates that even if the government could anticipate a decline in demand, the correct policy would still not require direct action to force the adoption of ring spinning. If the model is recalculated with a negative demand trend ($\alpha < 0$), then the appropriate policy during the booms of 1905-7 and 1911-12 would have been to invest in *neither* mules nor rings.[25] Intuitively, there was simply too much excess capacity to justify further expansion even allowing for the modest productivity advantage of rings at that time. And scrapping existing

[25] The model does not include the costs of managerial talent or the learning investment involved in establishing a vertically integrated organization. However, these additional costs and investments only make the case against investing stronger.

capacity (in a model that included a lower scrapping threshold) would only occur when price had fallen well below the levels observed during this period.

Other distortions and failures

Thus path dependence does not by itself imply any market failure or inefficiency even when there is lock-in to an inferior technology. But path dependence does makes technology transitions more difficult, and this may have the effect of *exacerbating* distortions or failures in other markets. This may be particularly true in situations where skilled labor is replaced—inadequate institutions for re-training workers and failures of credit and insurance markets for workers' incomes (which may cause private markets for training to fail) may slow the exodus of skilled workers from an industry (see Dixit and Rob [1994a,b] for formal models).

Such difficulties seem to have delayed the transition to ring spinning after 1920. Entry into skilled occupations in Britain at this time was primarily through formal apprenticeship programs and also informal learning in the form of "following up"—both largely oriented to training workers of age 21 and younger. Only a minority of skilled workers participated in formal technical education at all and this was typically supplemental to apprenticeship [More, 1980]. In any case, such technical education was rarely sufficient to gain entry into a skilled occupation. The opportunities for adult mule spinners to enter occupations of comparable skill and pay were necessarily limited by this arrangement. In addition, given the geographical concentration of cotton spinning in Lancashire, many opportunities would have required relocation.

Faced with limited re-training opportunities, mule spinners accepted sharply lower wages during the 1920's relative to other occupations [Jewkes and Gray, 1935]. Between June 1920 and June 1930 real piece rates for cotton spinning in Lancashire fell by 10% and real hourly earnings fell by 9%. Meanwhile real earnings for workers in all industries rose 9%.[26] That is, mule spinners accepted almost a 20% wage drop relative to similarly skilled peers.

Clearly, such a dramatic shift in labor costs would have affected firms' calculations for scrapping mules. In a model with a lower threshold (see Dixit and Pindyck [1994], chapter 8), firms choose to exit (scrap the old technology) when price falls below this threshold. The sharp drop in wages for spinners would have lowered this threshold, reducing the likelihood that mules

[26] The nominal rates and earnings are from Jewkes and Gray [1935]. The cost of living deflator and general wage level is from Dept. of Employment and Productivity [1971]. Jewkes and Gray provide evidence that the drop in cotton spinning rates and earnings was independent of any switch from mule spinning to ring spinning in the composition of the workforce.

would be scrapped. This in turn may have substantially prolonged the transition out of mule spinning. And, in fact, there were still more mule spindles than ring spindles in use in 1954 even in Oldham and other districts specializing in coarse spinning [Robson, 1957].

The welfare effect of this prolonged transition can be roughly estimated. Assume that spinners were paid their marginal product in 1920, that with re-training they could have generated a similar productivity in another industry, and that their productivity and wages would have grown in line with other workers after re-training.[27] Then the welfare loss incurred by keeping them from entering new occupations would have been roughly 20% of wages per annum less (one time) re-training costs. And because the transition was so prolonged, thanks in part to the uncertainty associated with path dependence, this loss would have accrued over many years to large effect.

If this analysis is correct, then government intervention could have improved welfare. The most obvious avenue for intervention, however, was not so much in directing the choice of technology, but rather in providing re-training and relocation incentives. In fact, the British government did intervene to encourage the scrapping of excess capacity in the 20's and 30's.[28] But when workers were unwilling to return to low wage spinning jobs after World War II, the government, concerned about a deteriorating balance of payments, perversely initiated efforts to train new spinners and to recruit greater employment *into* spinning [Singleton, 1991].

Of course a conclusive analysis of these suggested welfare losses is beyond the scope of this paper, but this argument illustrates the possibility of large losses. It has also been argued that the British educational system failed to produce sufficient managerial talent, raising the cost of vertical integration, and consequently delaying the adoption of ring spinning [Mass and Lazonick, 1990, Locke, 1984, Wrigley, 1988]. Similar considerations might apply here as well.

In any case, this analysis suggests more generally that although path dependence does not directly imply any inefficiency, the prolonged transition associated with path dependence may exacerbate welfare losses arising from incomplete markets and institutional barriers.

---

[27] If spinning wages had been elevated by union monopsony power, then this might overstate the gains to switching occupations. In this case, unions would have *accelerated* the transition to ring spinning. Nevertheless, this thumbnail calculation suggests the possibility of large welfare losses.

[28] The Lancashire Cotton Corporation, an amalgam created by a subsidiary of the Bank of England, scrapped 5 million spindles during the 20's and the Spindles Act of 1936 paid for the scrapping of 6 million additional spindles before World War II. As Lazonick argues, however, this did nothing to directly encourage a transition to ring spinning and integrated manufacture [Lazonick, 1983].

VI. Conclusion

Standard neoclassical models are about equilibrium conditions, not about transitions. It is not surprising therefore that simple models based on net present value calculations fail to capture major aspects of the transition to new technologies. The notion of path dependence, emphasizing the role of random events and the revelation of information over time, highlights an important shortcoming of these models.

Real options theory provides tools to analyze formally the adoption of new technologies under a very general and basic assumption about what economic actors know of the future of technology, namely that the profitability of technology evolves as a random walk. This, it is argued, is a very modest but appropriate description of what economic agents can know, one that is applicable to many technologies.

The resulting model provides a rich picture of technology evolution where both random historical events and economic profit-seeking behavior play substantive roles. Historical accident may cause firms to lock-in an inferior technology, but when the private benefit of switching technologies exceeds a threshold, firms do switch. Technology choice is not entirely at the mercy of random forces, but neither is it entirely the frictionless outcome of calculations based on current economic possibilities. In the end history does matter; options theory tells us just how much.

Appendix

Solution for deterministic industry model

This appendix requires familiarity with partial differential equations and Laplace transforms. The partial differential equation with boundary conditions (3) can be solved using a change of variables and Laplace transforms. Define

$$\tau \equiv v + T - t, \qquad q \equiv p \cdot e^{\mu \cdot (v+T-\tau)}, \qquad F(q,\tau) \equiv V(p,t).$$

These variables allow the Laplace transform to incorporate boundary condition (1) and to facilitate solution of the free entry condition. Using the new variables, (3) becomes

$$\begin{aligned} &-F_\tau(q,\tau) - r \cdot F(q,\tau) + q \cdot e^{\mu \cdot (v+T-\tau)} - c \cdot e^{-\mu v} = 0, \qquad 0 \le \tau \le T \\ &F(q,0) = 0, \quad F(\bar{q}, T) = e^{-\mu v} \end{aligned}.$$

Now define the Laplace transform with respect to τ as

$$\phi(q,\, s) \;\equiv\; L\big[F(q,\,\tau)\big] \equiv \int_0^\infty F(q,\,\tau)\cdot e^{-s\tau}\, d\tau\,.$$

Now it can be shown that $L\big[F_\tau(q,\,\tau)\big] = s\cdot\phi(q,s) - F(q,\,0) \;=\; s\cdot\phi(q,s)$, the last equality from the boundary condition. The transform of the entire differential equation is then

$$-s\cdot\phi(q,s) - r\cdot\phi(q,s) + \frac{q\cdot e^{-\mu(v+T)}}{s-\mu} - \frac{c\cdot e^{-\mu v}}{s} \;=\; 0.$$

This solves to

$$\phi(q,\, s) \;=\; \frac{q\cdot e^{-\mu(v+T)}}{(s+r)(s-\mu)} - \frac{c\cdot e^{-\mu v}}{s(s+r)}\;\;.$$

Taking the inverse transform (see any standard reference) and substituting back to the original variables yields

$$V(p,\,t) = \frac{p}{r+\mu}\cdot\Big(1-e^{-(r+\mu)(v+T-t)}\Big) - \frac{c\cdot e^{-\mu v}}{r}\cdot\Big(1-e^{-r(v+T-t)}\Big).$$

Application of the free entry condition at time $t = v$ then provides the expression for $\bar{p}(t)$.

Solving (6) only requires a single substitution:

$$\tau \equiv -t, \qquad\qquad G(p,\,\tau) \;\equiv\; U(p,\,t)\,.$$

Substituting, taking Laplace transforms incorporating the boundary condition for $\tau = 0$, solving for ϕ, and taking the inverse Laplace transform yields

$$U(p,\,t) \;=\; e^{rt}\cdot V(p,\,0)\Big|_{v=0} \;+\; \frac{p-c}{r}\cdot\Big(1-e^{rt}\Big), \qquad\qquad t \le 0\,.$$

Applying the free entry condition then yields (7).

Solution for stochastic industry model

To solve for the entry threshold, it is convenient to substitute variables as above:

$$\tau \equiv v + T - t, \qquad\qquad q \equiv p\cdot e^{\mu\cdot(v+T-\tau)}, \qquad\qquad F\big(q,\,\tau\big) \equiv V\big(p,\,t\big)\,.$$

The differential equation and boundary conditions become

$$\sigma^2\!/2\;\, q^2 F_{qq} + \alpha\, q\, F_q - F_\tau - r\,F + q\cdot e^{-\mu(v+T-\tau)} - c\cdot e^{-\mu v} \;=\; 0$$
$$F(q,0) = 0, \qquad F(0,\tau)\ \text{bounded}$$
$$F(\bar{q},T) = e^{-\mu v}, \qquad\qquad F_q(\bar{q},T) = 0$$

Note that the last two boundary conditions hold when $t = v$, or $\tau = T$. Taking the Laplace transform with respect to τ letting $L[F(q,\tau)] = \phi(q)$ and incorporating the first boundary condition as above,

$$\tfrac{1}{2}\sigma^2 q^2 \phi_{qq} + \alpha q \phi_q \; - (r+s)\phi + \frac{q \cdot e^{-\mu(v+T)}}{s-\mu} - \frac{c \cdot e^{-\mu v}}{s} \; = \; 0$$

(10) $$\phi(0) \text{ bounded}$$

$$\phi(\bar{q}) = \frac{e^{-\mu v}}{s}, \quad \phi_q(\bar{q}) = 0, \qquad \text{for } \tau = T$$

where the argument s has been suppressed in ϕ to emphasize that it is to be treated as a parameter in an ordinary differential equation. Taking account of the boundary condition on $\phi(0)$, this ODE solves to

$$\phi(q) \; = \; A \cdot q^{\beta} + \frac{q \cdot e^{-\mu(v+T)}}{(r+s-\alpha)(s-\mu)} - \frac{c \cdot e^{-\mu v}}{s(r+s)}, \quad \beta = \tfrac{1}{2} + \frac{-2\alpha + \sqrt{(2\alpha - \sigma^2)^2 + 8(r+s)\sigma^2}}{2\sigma^2}$$

where A is a constant to be determined.

Now it is possible to generate an equation for $\bar{q}$ using the last two boundary conditions of (10). Note that these conditions are only valid for $\tau = T$. However, it must be the case that an equation for $\bar{q}$ using these conditions will be valid if τ is equated to T after performing the inverse Laplace transform. Using these conditions to eliminate A yields

(11) $$\left(1 - \frac{1}{\beta}\right) \cdot \frac{\bar{q} e^{-\mu T}}{(r+s-\alpha)(s-\mu)} = \frac{1}{s} + \frac{c}{s(r+s)}.$$

To evaluate the inverse Laplace transform of this, consider the inverse transform of $1/\beta$:

$$L^{-1}\left[\frac{1}{\beta}\right] = \psi(\tau) = \frac{\sigma e^{-r\tau}}{\sqrt{2}} \cdot \left[-\gamma + \frac{e^{-\gamma^2 \tau}}{\sqrt{\pi \tau}} + \gamma \cdot \mathrm{Erf}\left(\gamma\sqrt{\tau}\right)\right], \qquad \gamma = \frac{\sigma^2 - 2\alpha}{2\sqrt{2}\sigma}$$

where Erf is the Gaussian error function. Using this, the inverse transform of (11) evaluated at $\tau = T$, generates

$$\bar{q} = \frac{r + \mu - \alpha}{1 - e^{-(r+\mu-\alpha)T} - e^{-\mu T} I(T)} \cdot \left(1 + \frac{c}{r}(1 - e^{-rT})\right),$$

where I is the convolution integral,

$$I(T) = \int_0^T \psi(t)\cdot\left(e^{\mu(T-t)} - e^{-(r-\alpha)(T-t)}\right) dt$$

$$= \frac{\sigma}{\sqrt{2}}\cdot\left[-\frac{\gamma e^{-rT}}{\alpha(r+\mu)}\left((r+\mu-\alpha)\left(1-\mathrm{Erf}\left[\gamma\sqrt{T}\right]\right)+\alpha e^{(r+\mu)T} - (r+\mu)e^{\alpha T}\right)\right.$$
$$-\left(1+\frac{\gamma^2}{\alpha}\right)\frac{e^{-(r-\alpha)T}}{\sqrt{\gamma^2+\alpha}}\mathrm{Erf}\left[\sqrt{T(\gamma^2+\alpha)}\right]$$
$$\left.+\left(1+\frac{\gamma^2}{r+\mu}\right)\frac{e^{\mu T}}{\sqrt{\gamma^2+r+\mu}}\mathrm{Erf}\left[\sqrt{T(\gamma^2+r+\mu)}\right]\right]$$

For typical values, $I > 0$. Substituting back, it follows then that $\bar{p}(t) = \bar{q}\cdot e^{-\mu t}$.

Mean time to adoption

Define $u \equiv \ln\frac{p}{\bar{p}(t)}$.

Then u follows an absolute Brownian motion as can be seen from Ito's Lemma,

$$du = \left[\frac{\partial u}{\partial t} + \alpha p\frac{\partial u}{\partial p} + \tfrac{1}{2}\sigma^2 p^2\frac{\partial^2 u}{\partial p^2}\right]dt + \sigma p\frac{\partial u}{\partial p}dz = \left(\mu+\alpha-\tfrac{1}{2}\sigma^2\right)dt + \sigma\, dz .$$

Now the expected wait period is the mean time required for u to go from $u = \ln\left(x/\bar{p}(0)\right)$ through a barrier at $u = 0$. Using the formula for expected first passage time this is

$$D(x) = \frac{1}{m+a-\frac{1}{2}s^2}\cdot\ln\left(\frac{\bar{p}(0)}{x}\right) \qquad \text{for} \qquad \mu+\alpha > \tfrac{1}{2}\sigma^2.$$

Bibliography

ARTHUR, W. BRIAN. “Competing Technologies: an overview,” in *Technical Change and Economic Theory*, Dosi, G. et al. eds., (New York: Columbia University Press, 1988).

ARTHUR, W. BRIAN. “Competing technologies, increasing returns and lock-in by historical events,” *Economic Journal*, XCIX (1989), 116.

BREMS, H. 1968. *Quantitative Economic Theory: a synthetic approach*, Wiley.

CABALLERO, R., AND PINDYCK, R. 1996. “Uncertainty, investment, and industry evolution,” *International Economic Review*, **37,** p. 641.

CHARI, V. AND HOPENHAYN, H. 1991. “Vintage human capital, growth and the diffusion of new technology,” *Journal of Political Economy*, **99,** p. 1142.

COPELAND, M. 1909. “Technical developments in cotton manufacturing since 1860,” *Quarterly Journal of Economics*, **24,** p. 109.

COPELAND, M. 1912. *The Cotton Manufacturing Industry of the United States,* Harvard University Press.

COX, D. R. AND MILLER, H. D. 1965. *The Theory of Stochastic Processes,* Methuen.

DANIELS, G. W. AND JEWKES, J. 1928. “The post-war depression in the Lancashire cotton industry,” *Journal of the Royal Statistical Society Part II,* **XCI,** p. 155.

DASGUPTA, P. AND STIGLITZ, J. 1981. “Uncertainty, industrial structure and the speed of R&D,” *Bell Journal of Economics,* **11,** p. 1.

DAVID, P. 1985. “Clio and the Economics of QWERTY,” *American Economic Review,* **75,** no. 2, p. 332.

DEPT. OF EMPLOYMENT AND PRODUCTIVITY, GREAT BRITAIN. 1971. *British Labour Statistics: Historical Abstract,* HMSO.

DIXIT, A. 1993. “The Art of Smooth Pasting,” in *Fundamentals of Pure and Applied Economics,* **55,** Harwood.

DIXIT, A. AND PINDYCK, R. 1994. *Investment Under Uncertainty,* Princeton University Press.

DIXIT, A. AND ROB, R. 1984a. “Risk-sharing, adjustment and trade,” *Journal of International Economics,* **v. 36,** p. 263.

DIXIT, A. AND ROB, R. 1984b. “Switching costs and sectoral adjustments in general equilibrium with uninsured risk,” *Journal of Economic Theory,* **v. 62,** p. 48.

FARNIE, D. 1990. “The textile machine-making industry and the world market, 1870-1960,” *Business History,* p. 150.

FRANKEL, M. 1955. “Obsolescence and technological change in a maturing economy,” *American Economic Review,* **45,** p. 296.

GOOLSBEE, A. 1998. “The business cycle, financial performance, and the retirement of capital goods,” *NBER Working Paper,* **No. 6392.**

GREENE, W. 1997. *Econometric Analysys,* 3rd edition, New Jersey: Prentice Hall.

JENSEN, R. 1982. “Adoption and diffusion of an innovation of uncertain profitability,” *Journal of Economic Theory,* **27,** p. 182.

JEWKES, J. AND GRAY, E. 1935. *Wage and Labour in the Lancashire Cotton Spinning Industry,* Manchester University Press.

JONES, G. T. 1933. *Increasing Returns,* Cambridge University Press.

JOVANOVIC, B. AND LACH, S. 1989. “Entry, exit and diffusion with learning by doing,” *American Economic Review,* **79,** p. 690.

JOVANOVIC, B. AND MACDONALD G. 1994. “Competitive Diffusion,” *Journal of Political Economy***,** p. 24.

KAMIEN, M. AND SCHWARTZ, N. 1972. “Some economic consequences of anticipating technical advance,” *Western Economic Journal,* **10,** p. 123.

LAZONICK, W. 1981. “Factor costs and the diffusion of ring spinning in Britain prior to World War I,” *Quarterly Journal of Economics,* **96,** p. 89.

LAZONICK, W. 1983. “Industrial organization and technological change: the decline of the British cotton industry,” *Business History Review,* **57,** p. 195.

LAZONICK, W. 1987. “Stubborn mules: some comments,” *Economic History Review,* **40,** p. 80.

LAZONICK, W. 1992. *Organization and Technoloy in Capitalist Development,* Elgar.

LAZONICK, W. AND MASS, W. 1984. “The performance of the British cotton industry, 1870-1913,” *Research in Economic History,* **9,** p. 1.

LIEBOWITZ, S. AND MARGOLIS, S. 1990. "The Fable of the Keys," *Journal of Law and Economics,* **33,** p. 1.

LIEBOWITZ, S. AND MARGOLIS, S. 1995. "Path dependence, lock-in and history," *Journal of Law, Economics and Organization,* **11,** p. 205.

LOCKE, R. 1984. *The End of the Practical Man: entrepreneurship and higher education in Germany, France and Great Britain, 1880-1940,* Greenwich Connecticut: JAI Press.

MASS, W. 1989. "Mechanical and organizational innovation: the Drapers and the automatic loom," *Business History Review,* **v. 63,** p. 876.

MASS, W. AND LAZONICK, W. 1990. "The British cotton industry and international competitive advantage: the state of the debates," *Business History,* **32,** p. 9.

MCCARDLE, K. F. 1985. "Information acquisition and the adoption of new technology," *Management Science,* **31,** p. 1372.

MOKYR, J. 1998. "The political economy of technological change: resistance and innovation in economic history," in Berg, M. and Bruland, K. eds. *Technological Revolutions in Europe: historical perspectives,* Cheltenham, UK: Edward Elgar.

MORE, C. 1980. *Skill and the English Working Class, 1870-1914,* New York: St. Martin's Press.

PARENTE, S. 1994. "Technology adoption, learning by doing and economic growth," *Journal of Economic Theory,* **63,** p. 346.

PAYNE, P. L. 1988. *British Entrepreneurship in the Nineteenth Century,* Macmillan.

ROBSON, R. 1957. *The Cotton Industry in Britain,* Macmillan.

ROSENBERG, N. 1976. "On technological expectations," *Economic Journal,* **86,** p. 523.

RYAN, J. 1930. "Machinery replacement in the cotton trade," *Economic Journal,* **40,** p. 568.

SALTER, W. 1969. *Productivity and Technical Change,* Cambridge University Press.

SANDBERG, L. 1974. *Lancashire in Decline: a study in entrepreneurship, technology and international trade,* Ohio State University.

SAXONHOUSE, G. AND WRIGHT, G. 1984a. "Rings and mules around the world: a comparative study in technological choice," *Research in Economic History,* **Supplement 3,** p. 271.

SAXONHOUSE, G. AND WRIGHT, G. 1984b. "New evidence on the stubborn English mule and the cotton industry, 1878-1920," *Economic History Review,* **37,** p. 507.

SAXONHOUSE, G. AND WRIGHT, G. 1987. "Stubborn mules and vertical integration: the disappearing constraint?," *Economic History Review,* **40,** p. 87.

SCHMOOKLER, J. 1966. *Invention and Economic Growth,* Harvard University Press.

SINGLETON, J. 1991. *Lancashire on the Scrapheap: the cotton industry 1945-1970,* Oxford University Press.

US DEPARTMENT OF AGRICULTURE. *Statistics on Cotton and Related Data,* Statistical bulletin.

WEISS, A. 1994. "The effects of expectations on technology adoption: some empirical evidence," *Journal of Industrial Economics,* **42,** p. 341.

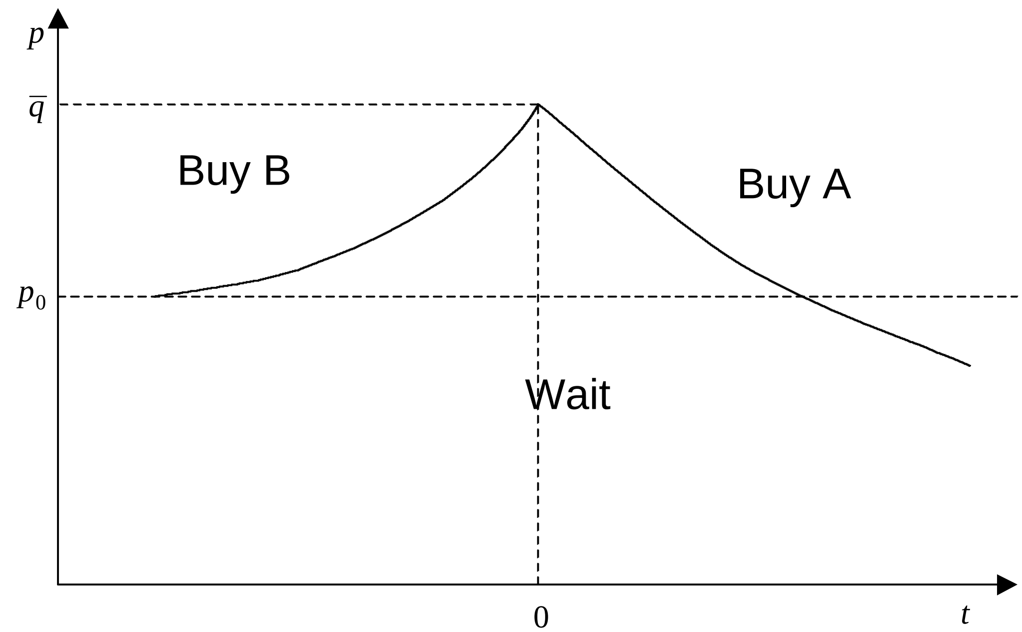
WILLIAMSON, J. 1968. "Optimal replace of capital goods: the early New England and British textile firm," *Journal of Political Economy,* **76,** p. 1320.

WINTERBOTTOM, J. 1907. *Cotton Spinning Calculations and Yarn Costs,* Longmans.

WRIGLEY, J. 1985. "Technical education and industry in the nineteenth century," in Elbaum, B. and Lazonick, W. eds. *The Decline of the British Economy,* Oxford: Clarendon Press.

Figure 1. Price Entry Threshold for Industry with Free Entry

A. Regions of action / inaction



B. Random paths, two leading to adoption of new technology, one to permanent "lock in"

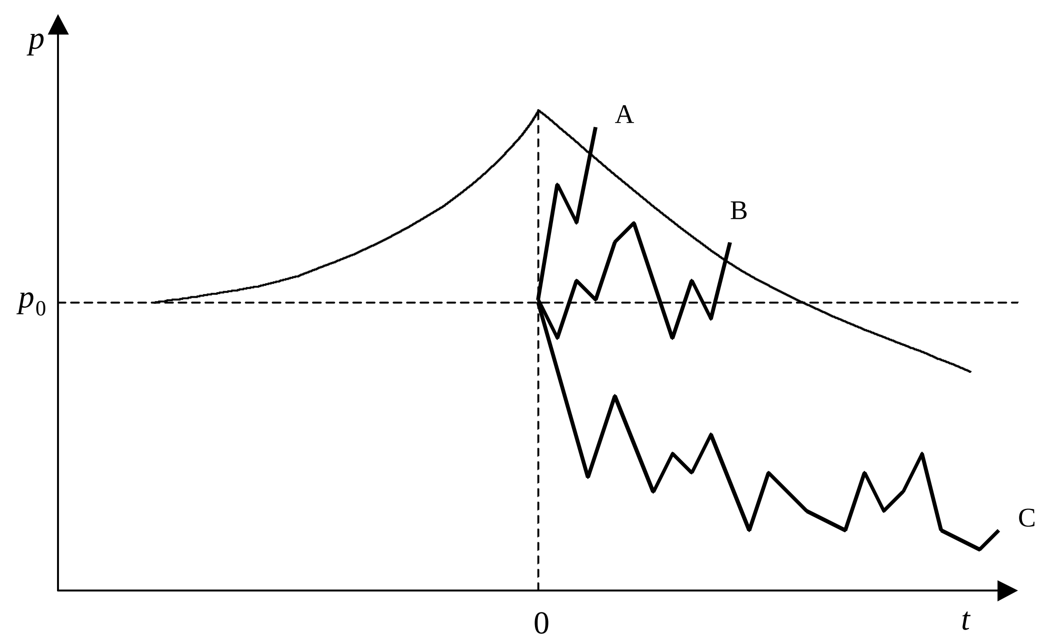


Figure 2. Actual Margin for 32s Yarn in Pence/lb. and Calculated Entry Thresholds
Source: Margin data from Robson [1957] with adjustments for waste and selling expense from Winterbottom [1907] The years after 1915 experienced constrained production and rapid war-related inflation and so these years have been omitted from the figure. Since cotton prices are largely determined after the harvest (September to November), yet equipment will be purchased based on anticipated demand, equipment purchases should correspond most closely with the average prices of the following year. The figures in the chart have been shifted one year earlier to account for this.

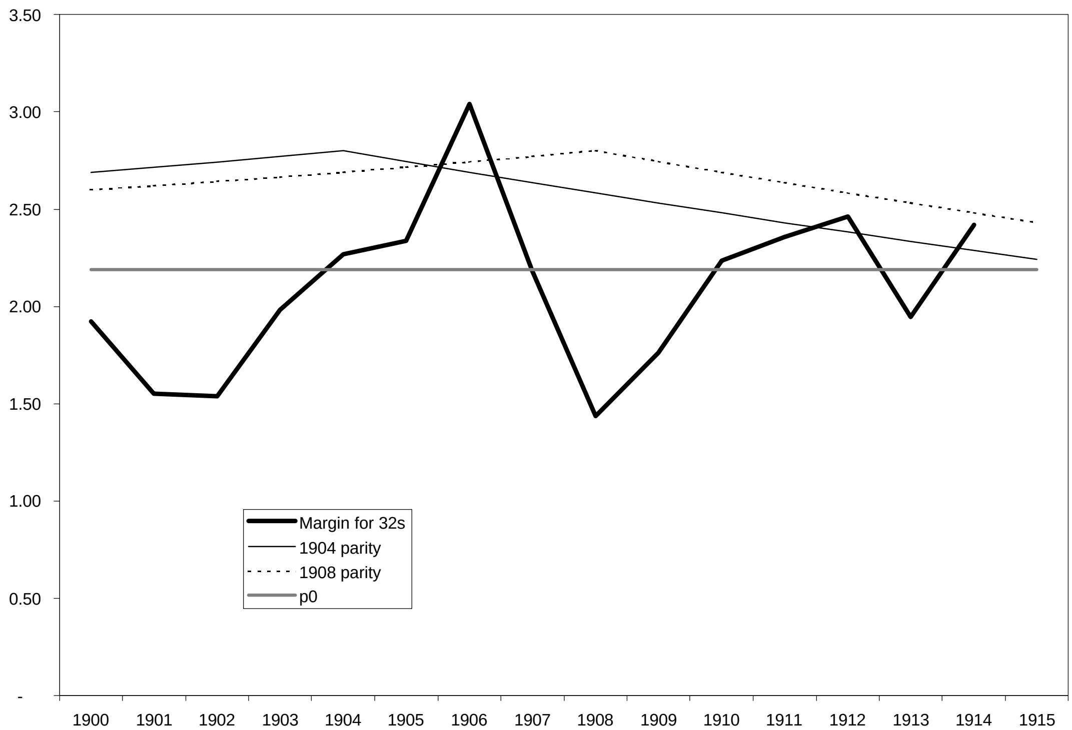


Figure 3. Orders for mule and ring spindles for production below 40s.
Data derived from order books of 6 large British textile equipment manufacturers as reported in Saxonhouse and Wright [1984a,b]. These sources report the annual total orders by spindle type. Gary Saxonhouse provided supplementary data listing the annual quartiles of the distribution of yarn count by spindle type for those orders that specified an intended count. These data were interpolated (details available from author) to obtain the percentage of spindles of each type intended for sub-40 production each year. These percentages were then applied to the total annual orders by spindle type. Note that production resources were re-directed to munitions manufacture beginning in 1915 and supplies were still constrained during the boom of 1919-20.

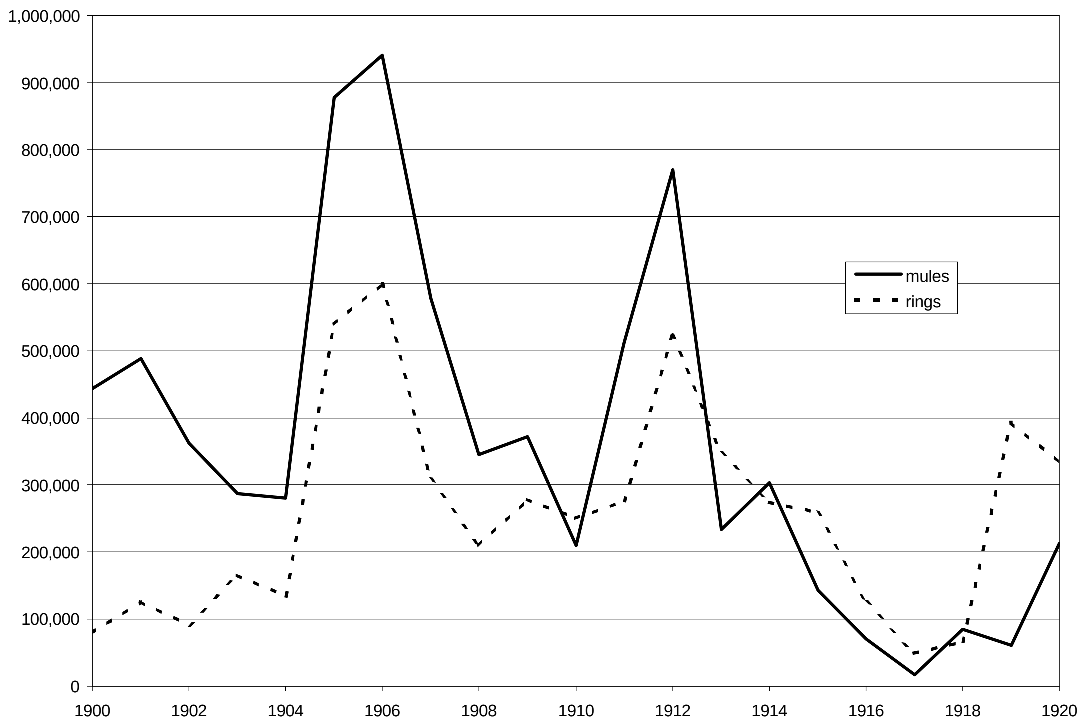


Figure 4. Ring spindles as a percent of new domestic spindle orders;
Five year centered moving average.

Source: Data are described in the previous figure. Moving average is calculated as the sum of ring spindles ordered in the 5 year interval divided by the total spindles ordered during this interval.

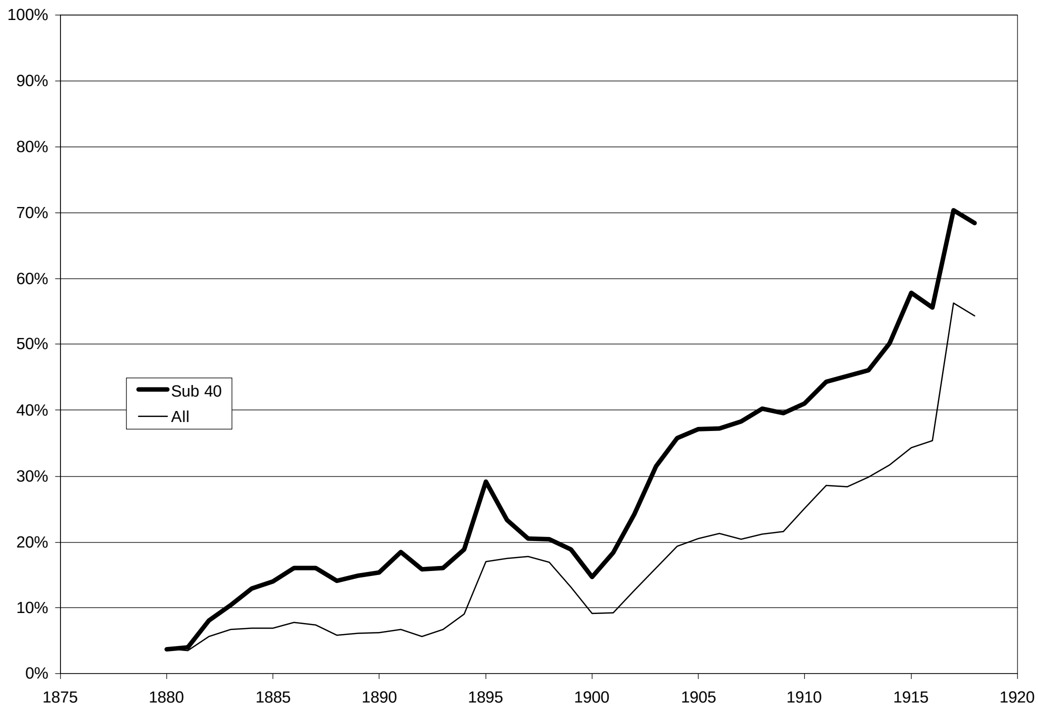


Table 1. Threshold Parameters and Mean Durations for Industry with Free Entry

Interest rate r	Demand growth rate α	Productivity growth rate (tech. A) μ	$\bar{q}$	Max. price distortion $\frac{\bar{q}-p_0}{p_0}$	Mean time to first adoption $D(p_0)$ years	Mean equipment life T years
0.05	0.03	0.005	0.17	8%	5.4	241.3
0.05	0.03	0.010	0.18	17%	7.8	128.0
0.05	0.03	0.020	0.20	32%	9.3	70.2
0.05	0.03	0.030	0.22	45%	9.4	50.0
0.05	0.03	0.040	0.24	58%	9.1	39.5
0.10	0.03	0.005	0.22	4%	2.8	295.5
0.10	0.03	0.010	0.23	9%	4.2	151.8
0.10	0.03	0.020	0.25	17%	5.3	79.7
0.10	0.03	0.030	0.26	26%	5.7	55.5
0.10	0.03	0.040	0.28	34%	5.9	43.2
0.05	0.01	0.020	0.22	28%	24.9	74.8
0.05	0.01	0.030	0.24	40%	16.8	52.8
0.05	0.01	0.040	0.26	50%	13.6	41.3
0.10	0.01	0.020	0.26	16%	15.0	82.7
0.10	0.01	0.030	0.28	24%	10.8	57.3
0.10	0.01	0.040	0.30	32%	9.2	44.5

Note: $\sigma^2 = .04$, $c = .05$. Variables are described in the text. $\bar{q}$ is the price entry threshold at time zero; p_0 is the price threshold had there been no new technology; D is mean period from time zero to the first investment in new technology, assuming price equals p_0 at time zero; T is expected equipment life (no physical depreciation).

Table 2. Additional Parameter Values for Industry with Free Entry.

Interest rate r	Demand variance σ^2	Operating costs c	$\bar{q}$	Max. price distortion $\frac{\bar{q} - p_0}{p_0}$	Mean time to first adoption $D(p_0)$ years	Mean equipment life T years
0.05	0.001	0.05	0.16	55%	7.4	38.4
0.05	0.020	0.05	0.19	50%	8.2	45.2
0.05	0.040	0.05	0.22	45%	9.4	50.0
0.05	0.040	0.10	0.32	40%	8.4	39.1
0.10	0.040	0.05	0.26	26%	5.7	55.5
0.10	0.040	0.10	0.35	25%	5.6	41.8
0.10	0.040	0.15	0.44	25%	5.5	35.6

Note: $\mu = .03$, $\alpha = .03$. Variables described in text and above.

Table 3. Typical Costs for Spinning Medium Yarn in Southeast Lancashire circa 1905 Excluding Base Cotton cost, Cotton Waste and Selling Discount/Expense

Category	**Mule** pence / lb.	**Ring** **Warp yarn or weft in integrated mill** pence / lb.
Labor	.73	.48
Coal	.08	.10
Misc. supplies	.10	.10
SUBTOTAL – Variable costs	.91	.68
Maintenance	.09	.09
Utilities	.02	.02
G&A	.03	.03
Taxes	.04	.04
Insurance	.01	.01
Interest at 5%	.31	.27
Depreciation at 2%	.12	.10
SUBTOTAL –Fixed costs	.61	.56
Premium for long staple cotton	--	.25
TOTAL	**1.52**	**1.49**

Sources: Winterbottom [1907] for mule data and Lazonick [1981] for adjustments for rings. The calculations have been made for 32s yarn with an assumed output of .98 lb. per spindle per 56.5 hour week for mules [Lazonick, p. 107]. Rings required slightly longer staple cotton than mules. For 32s yarn this difference was about 1/16 inch which entailed about a price premium of about 0.25d [Sandberg, 1974], although this would fluctuate depending on market conditions. This premium has tended to average about 5% historically despite major changes in production of longer staple cotton [USDA]. This calculation assumes that ring spinners would have used all cotton of longer staple. In fact, cotton mixing was standard practice and this would have lowered the effective cost differential and improved the relative cost advantage of ring spinning.