# Real Options and the Adoption of New Technologies

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Version: 12/99

New technologies typically improve over time. Firms adopting new technologies expect future vintages to be superior, and, with free entry, to bring lower prices. Hence firms may value the option to wait before making irreversible investment. Traditional means of accounting for obsolescence do not fully capture these considerations. This paper develops a real options model for investment in new technology. Even modest rates of incremental improvement lead firms to raise investment thresholds substantially. This typically delays first adoption for many years. Thresholds are affected by the rate of productivity improvement, interest rates, demand growth and price uncertainty. As an application, investment thresholds are calculated for the adoption of new spinning technology in the British cotton industry at the turn of the century.

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## 1 INTRODUCTION

Since the Industrial Revolution firms have had to reckon with the problem of technological obsolescence. Williamson (1971) provides evidence that American ante bellum textile firms, faced with more rapid rates of technological change than their British counterparts, followed replacement policies that led to more rapid scrapping of equipment. How should one account for ongoing technological progress when considering the purchase of new technology?

Economists often assume that a firm needing new equipment will purchase outright the most advanced technology available at the time. The frictionless acquisition of new technologies is a common modeling assumption. But, in fact, firms do have an alternative: they can 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, the option value of waiting may be significant. Expectations about future productivity growth and related price changes may substantially alter the decision to invest. A firm considering investment in new technology must wrestle with a difficult tradeoff of whether to buy now or buy later. The firm marketing a new technology needs to accurately gauge how rapidly it will be adopted—all too many product managers have been frustrated by new products that seemed to offer clear-cut advantages, yet failed to gain rapid acceptance.

One way firms have accounted for technological obsolescence is to use a depreciation rate in excess of the actual rate of equipment failure or decline in capital services. This generates an elevated hurdle rate for evaluating improving technologies. However, there are no clear guidelines for choosing such an accelerated depreciation rate or an elevated discount rate. Attempts to infer a depreciation rate from observed equipment lives seriously understate the value of waiting and hence provide too low a hurdle rate.

Real options methods now provide managers a better means to make technology adoption decisions, to gauge conditions for the acceptance of new technology more accurately, and to understand which market segments might be most likely to adopt. This paper explores the adoption of new, improving technologies using a rather simple options model. These methods are applied to a case of technological switching that has interested economic historians: the conversion from mule spinning to ring spinning in the early twentieth-century British cotton industry.

Surprisingly, the options model demonstrates that a new technology with a moderate expected annual rate of productivity improvement (of just a few percent) can experience substantial adoption delays and price distortions even in a competitive market. Specifically, the threshold price necessary for investment can increase substantially for many years. Barring large exogenous demand increases, this means that firms will forego new investment for years. Rather than adopting a new technology as soon as it becomes marginally profitable, firms will typically not adopt until the new technology is *substantially more* profitable than the old technology. Firms will also forego investment in the old technology while it is still more profitable than the new technology.

Economic models tend to view technological change *either* as a discrete switch of technologies *or* as a steady stream of incremental improvements. In the first case, technological change is treated as a sudden "technology shock," to which economic variables slowly adjust; in the latter case, it is treated as continuous change often at a fixed rate of productivity growth. Yet in reality, both sorts of change may occur concurrently. Discrete new technology shifts are typically accompanied by changes in the *rate* of incremental improvement. Mature technologies, such as mule spinning circa 1900, tend to be stagnant, while emerging new technologies, such as ring spinning, often experience sequential improvement.

This is because new technologies seldom first appear in their final forms, but rather they typically experience incremental improvements in quality and productivity. Gort and Klepper (1982) found a significant number of recorded innovations following the introduction of new technologies, and these were probably accompanied by numerous unrecorded minor improvements. Sequential innovation, learning-by-doing, and learning-by-using contribute to gradual productivity growth of new technologies especially during the initial decades. Enos (1962) found that most of the productivity gains of new petroleum refining technologies were achieved during the decades following introduction. As technologies mature, frequently the rate of incremental improvement declines.

Firms contemplating the adoption of a new technology are, of course, aware of this pattern of sequential improvement. They consider not only the current productivity level of the new technology, but also expectations of future productivity. Two sorts of expectations may affect their investment decisions. First, firms expect future vintages of the new technology to be more productive. Second, to the extent that entry into the market is unrestricted and that the technology is available to other prospective entrants, firms expect future vintages to be accompanied by lower entry thresholds and hence lower prices. This paper focuses on situations where the technology is not proprietary and where market entry is not restricted.

The role of such expectations on a single, incrementally improving technology has been previously explored. Jeffrey Williamson (1971) and Brems (1968) examined the influence of technology expectations on equipment obsolescence and this model is nested within the model 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.[1] Rosenberg (1976) cites several historical cases where technological expectations delayed adoption.

There are many explanations for the long delays often observed in the adoption of new technologies. Much of the neoclassical literature on adoption has stressed the role of sunk costs in existing technology (Salter, 1966) or in complementary technologies (Frankel, 1955). Note that the analysis developed here applies both to the replacement of existing technology and also to the adoption of new 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; Jovanovic and Lach, 1989), and search costs (Jovanovic and MacDonald, 1994). Note that the delays described in this paper occur without any such complementary costs and may act to magnify the differential effects of such costs.

Another explanation for slow adoption is provided by strategic considerations where market power may allow incumbents to delay adoption (e.g., Dasgupta and Stiglitz, 1980). The model developed here applies, instead, to markets with free entry. As long as the new technology is widely available and does not confer major first-mover advantages, free entry provides the least support for strategic delay.

The paper is organized as follows: The next section presents some background and assumptions. Section 3 develops an industry model with free entry using the new technology. Section 4 applies the model to the British transition to ring spinning. Section 5 concludes.

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

# 2 BACKGROUND

## 2.1 An Example

Consider a noted example of technology adoption that has received substantial attention from economic historians.[2] During the first decade of the twentieth century, British cotton spinners continued to invest predominately in intermittent spinning technology (mule spinning) even though continuous technology (ring spinning) was steadily gaining an advantage. The 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 it completely dominated the British industry. However, advances in ring spinning continued, especially in America. 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 have been better to wait. The investment decision could not be based solely on static comparisons; the entrepreneur also had to consider uncertain expectations about what improvements were likely in the near future. This implies an option value to waiting that may dramatically affect the timing and nature of adoption.

To account for anticipated obsolescence, managers have in the past often increased depreciation allowances. 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 (in addition to equipment maintenance charges). 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 have also used this ad hoc adjustment. For example, Sandberg (1974), in his study of ring versus mule spinning, applies a depreciation rate of 10% to spinning equipment to

[2] An overview of the debate can be found in Payne (1990) and in Lazonick and Mass (1990).

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 apply, such rules of thumb are ad hoc and ultimately unsatisfying. For one thing, an obsolescence-based depreciation rate does not capture adequately everything that affects a firm's profit flow. It does not directly relate to the effect of technology on uncertain prices. More generally, there are no clear guidelines for estimating such an enhanced depreciation rate—is it 4% above the interest rate, 10% above or something higher? Although one can observe the distribution of equipment lives, this is insufficient to deduce an accurate hurdle rate as demonstrated below. Options analysis helps provide a more rigorous means for determining the appropriate hurdle rate.

## 2.2 Assumptions

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 (e.g., mule versus ring spinning), but machines cannot be retrofitted with newer technology. The new technology is labeled A and the old technology is labeled B. The old technology is assumed to be mature and thus does not improve over time.

Technology A does improve over time and these improvements are assumed to be Hicks-neutral.[3] Also, we assume that the machine-making industry is sufficiently competitive and has sufficiently stable costs so that the benefits of productivity improvement are passed entirely to the industry using the machines. We 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 $c$. Assume that both the equipment cost and operating cost necessary to produce a unit of output decrease at an expected rate $\mu$ for each new vintage. Technology improvement could be modeled as a stochastic (Poisson) process, however this adds little to the analysis 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.

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

[3] That is, as a simplifying assumption, the ratio of equipment costs to operating costs remains fixed.

for reasons of technological obsolescence. This is a strong simplifying assumption, but adding stochastic retirements does not materially alter the results. Moreover, there is evidence that retirements are driven substantially by obsolescence (Williamson 1971, Goolsbee 1998).[4]

Finally, investment is considered irreversible. There are at least two justifications for this assumption. First, new technologies frequently have large adoption costs. These are substantially 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.

## 3 INDUSTRY EQUILIBRIUM DYNAMICS

### 3.1 Stochastic Model of Price and Entry

This analysis 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). In their model, industry demand follows a geometric random walk with drift. Also, new firms are free to enter and they will choose to do so as long as the discounted expected profits for an active firm exceed the cost of entry. Since expectations of future profits depend on current output price, there exists a threshold price, $\overline{p}$ , such that the value of entering just equals the cost of entry at this price. If price momentarily exceeds this threshold, new firms will rapidly enter, driving price below the threshold again. Technically, $\overline{p}$ is an upper reflecting boundary. Below the threshold industry capacity remains fixed and price, following demand shocks, evolves as a geometric random walk.

Consideration of technical change adds a twist to this model: new entrants can utilize the newest, most productive vintage of technology. The task is to calculate the entry price threshold considering this enhancement. Now the entry threshold will change over time because costs change, so it can be written $\overline{p}(t)$ .We obtain the threshold price first for the domain where technology A is superior. Then we obtain a solution for the domain where the older technology B is superior, subject to a condition that the two solutions match at the time when the two technologies are equally productive.

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4 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.

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. An entrant will want to purchase the best available vintage, so $v = t$. Let $p$ be the product price, a stochastic variable, and let $c \cdot e^{-\mu v}$ be the unit operating cost for this vintage of technology, with $e^{-\mu v}$ being the cost of equipment of this vintage sufficient to produce one unit output per annum.

Below the price threshold, $\bar{p}(t)$, $p$ will evolve as a geometric random walk with drift, reflecting random shocks to demand. That is, in this domain $p$ follows a geometric Brownian motion with drift $\alpha$ and standard deviation $\sigma$:

$$dp = \alpha\ p\ dt\ +\ \sigma\, p\ dz \tag{1}$$

where $dz$ is a Wiener process.

Now the value of an active firm depends on the current price and time. Let $V(p, t; v)$ represent the value of an active firm at time $t$ with technology A of vintage $v$. Consider this value in the domain where $p < \bar{p}(t)$. Using the Bellman principle to separate this value into flow and capital gains components, and letting $r$ represent the risk-adjusted discount rate,[5]

$$V(p, t; v) = \left(p - c \cdot e^{-\mu v}\right) dt + \frac{E\left[V(p + dp,\ t + dt; v)\right]}{1 + r\ dt} \tag{2}$$

Then, using Ito's Lemma

$$E\left[V\left(p + dp, t + dt\right)\right] = V(p, t) + \alpha\ p\, V_p(p, t)\, dt + \tfrac{1}{2}\sigma^2 p^2 V_{pp}(p, t)\, dt + V_t(p, t)\, dt \tag{3}$$

with subscripts denoting partial derivatives and suppressing the notation for vintage.

Inserting (3) into (2), re-arranging, and dropping lower order terms, such as $(dt)^2$, this yields the partial differential equation

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

Boundary conditions may be obtained from consideration of entry and exit. First, at the entry threshold the value of an active firm with the latest vintage must equal the cost of entry. That is,

[5] The Capital Asset Pricing Model is assumed to hold and so $r$ is the required rate of return given the degree of non-diversifiable risk (risk free rate plus risk premium).

$$V\left(\bar{p}(v), v; v\right) = e^{-\mu v}.$$

Also, since this threshold is a reflecting boundary, a standard property of any reflecting boundary is the “smooth pasting” condition (see Dixit, 1993, pp. 26-7), namely that

$$V_p\left(\bar{p}(v), v; v\right) = 0.$$

Now note that $\bar{p}(t)$ is a declining function of $t$. Firms that enter later 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. Define $T$ as the point where a firm with vintage $v$ cannot possibly make a profit because of obsolescence. Since the operating costs for this firm are $c \cdot e^{-\mu v}$, $T$ must solve

$$\bar{p}(v+T) = c \cdot e^{-\mu v}. \tag{4}$$

This firm will only be active during the interval $v \le t \le v+T$. It is possible that a firm might choose to exit prior to time $v + T$, for instance, if price fell sufficiently. To consider this possibility, the model would also have to include a lower price exit threshold for each vintage of technology. This would considerably complicate the model. Note, however, that if $c$ is not too large and $\alpha$ is not too negative, then there is only a small probability that the firm would want to exit much before time $T$. As a first order approximation, we assume that a prospective entrant with vintage $v$ technology will anticipate exiting at time $v + T$.[6] This implies the boundary condition on $V$:

$$V\left(p, v+T; v\right) = 0.$$

Also, in lieu of an exit threshold, we impose the simple condition that $\lim_{p \to 0} V(p,t;v)$ is bounded.

Thus for the domain where technology A is superior, the partial differential equation and boundary conditions can be summarized:

[6] If all firms actually exit at this time, a potential inconsistency arises: if a large portion of industry capacity is all scrapped at a given time (say when old technology B becomes obsolete at time $t = T$), then this will surely influence price. For consideration of price expectations, we assume that there is sufficient uncertainty about scrapping dates so that the assumption of a random walk can be maintained. That is, firms plan on their own exit after $T$ years, but do not explicitly attempt to calculate the influence on price of similar exit behavior among other firms. This is a reasonable approximation because we are primarily interested in adoption behavior during the first few years after the new technology becomes superior.

$$
\begin{array}{ll}
\tfrac{1}{2}\sigma^2\, p^2 V_{pp} + \alpha\, p V_p + V_t - rV + p - c\cdot e^{-\mu v} = 0 & \\
V\left(p, v+T; v\right) = 0, & \lim_{p\to 0} V\left(p, t; v\right) \text{ bounded} \\
V\left(\overline{p}(v), v; v\right) = e^{-\mu v}, & V_p\left(\overline{p}(v), v; v\right) = 0 \\
0 \le v \le t \le v+T, & 0 < p \le \overline{p}(t)
\end{array}
\qquad (5)
$$

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

$$
\begin{aligned}
&\overline{p}(t) = \overline{q}\cdot e^{-\mu t}, \\
&\overline{q} \equiv \frac{r+\mu-\alpha}{1-e^{-(r+\mu-\alpha)T} - e^{-\mu T} I(T)} \cdot \left(1+\frac{c}{r}\left(1-e^{-rT}\right)\right), \qquad r+\mu > \alpha
\end{aligned}
\qquad (6)
$$

where $I(T)$ is described in the Appendix. Given this, (4) can be solved numerically for $T$. Note that as $\sigma$ approaches zero, this solution reverts to the same solution Williamson (1971) found for a non-stochastic model.

It remains to find the entry threshold at $t < 0$, when old 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

$$\tfrac{1}{2}\sigma^2\, p^2 U_{pp} + \alpha\, p U_p + U_t - rU + p - c = 0\ .$$

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

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

Also, 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:

$$U\left(p, 0\right) = V\left(p, 0; v=0\right).$$

Adding corresponding smooth pasting and lower bound conditions, the differential equation with boundary conditions for old technology B can then be summarized as follows:

$$
\begin{array}{ll}
\tfrac{1}{2}\sigma^2 p^2 U_{pp} + \alpha p U_p + U_t - rU + p - c = 0, & t \le 0, \quad 0 < p \le \overline{p}(t) \\
U(p, 0) = V(p, 0; v=0), & \lim_{p\to 0} U(p,t) \text{ bounded} \\
U\left(\overline{p}(t), t\right) = 1, & U_p\left(\overline{p}(t), t\right) = 0
\end{array}
\qquad (7)
$$

Obtaining an analytic solution to this equation is difficult, however, an approximation is (see Appendix):

$$\bar{p}(t) \approx p_0 \cdot \left(1 - e^{rt}\right) + \bar{q} \cdot e^{rt}, \qquad t < 0$$

$$p_0 \equiv \frac{\beta}{\beta - 1} \cdot (r - \alpha) \cdot \left(1 + \frac{c}{r}\right), \qquad \beta \equiv \tfrac{1}{2} + \frac{-2\alpha + \sqrt{(2\alpha - \sigma^2)^2 + 8r\sigma^2}}{2\sigma^2}.$$

### 3.2 Characteristics of the Solution

The general characteristics of the entry threshold are displayed in Figure 1 and Tables 1 and 2 present results for a range of parameter values. The optimal decision rule corresponding to this threshold is as follows: if price is below the threshold, then wait. If price exceeds the threshold and $t < 0$, the purchase technology B. If price exceeds the threshold and $t \geq 0$, then purchase technology A.

Long before technology A achieves parity with the old technology B, the threshold approximates $p_0$, the price threshold that would obtain if there were no technology other than B. As technology A approaches technology B in productivity, the price threshold rises. Intuitively, prospective entrants will require a higher price in order to invest irreversibly in technology that is soon to become obsolete. This increase in the threshold around the transition time can be attributed to the increased value of the option to wait, although this option has not been explicitly calculated. Once technology A surpasses technology B, the price threshold declines at rate $\mu$, as the cost of entry progressively decreases.

The elevation of the threshold around $t = 0$ means that in general investment will be less likely during this time and that the first adoption of technology A may not occur until well after it surpasses technology B. The timing of any given technology transition depends on the actual random fluctuations of price that occur. However, several general characteristics can be calculated.

First, the extent of the price distortion around the transition time can be measured by comparing the entry threshold at $t = 0$, $\bar{p}(0) = \bar{q}$, to the entry threshold that would exist if technology B were the only technology, $p_0$. 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 $\mu$, the rate of productivity growth of technology A.

The period during which the entry threshold is elevated above $p_0$ can be thought of as a "waiting period," considering that prospective entrants are more likely to wait. The beginning of the wait period is ill-defined because it depends on the time when firms first become aware of technology A. However one can estimate the wait period after technology A surpasses technology

B. The expected duration of this waiting period depends on the initial price at time zero. As a benchmark, the expected wait period can be calculated for a price of $p_0$ at time zero. Define

$$u(p,\,t) \;\equiv\; \ln\frac{p}{\overline{p}(t)}.$$

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

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

The expected wait period is the mean time required for $u$ to go from $u = \ln\left(p_0 / \overline{p}(0)\right)$ through a barrier at $u$ = 0. Using the formula for expected first passage time, this is[7]

$$D = \frac{\ln\left(\dfrac{\overline{p}(0)}{p_0}\right)}{\mu + \alpha - \frac{1}{2}\sigma^2} \qquad \text{for} \qquad \mu + \alpha > \tfrac{1}{2}\sigma^2\,.$$

These values are also listed in Tables 1 and 2. If $\mu + \alpha$ fails to meet the condition, then there is a positive probability that price may never exceed the entry threshold and technology A will *never* be adopted. Assume that is not the case.

Even with certain adoption, 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, $\mu$ has a dramatic effect on equipment life as Williamson (1971) argued. The difference between $T$ and the expected first passage time, $D$, 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 follows:

> *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

[7] See (Cox and Miller, 1965) or (Dixit, 1993).

(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, $\mu$, significantly postpone the mean time to first adoption of the new technology. Even very modest values of $\mu$ can generate significant lags. On the other hand, increases in $\mu$ 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, $\alpha$, also dramatically decreases time to first adoption and modestly decreases expected equipment life.

4. Greater uncertainty, represented by larger $\sigma$, 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 for firms marketing new technologies. Assuming small private firms are more liquidity-constrained, 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 sometime argued that low interest rates spur adoption of embodied technology by lowering user cost. The analysis here suggests an opposing effect. Although lower interest rates do lower the user cost of new equipment, 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 incentives 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.

Finally, the above model assumes that the expected rate of productivity growth for the new technology, $\mu$, is exogenous. Yet there are, in fact, at least two reasons why the rate of productivity growth may 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. A model incorporating these dynamic effects is beyond the scope of this paper.

## 4 AN APPLICATION: RING SPINNING VERSUS MULE SPINNING

The usefulness of the real options approach is illustrated with data for a hypothetical cotton spinner circa 1905. We calculate the relevant parameters for a prospective British spinner of 32s warp yarn to apply the model for an industry with free entry.[8] This industry was manifestly one with few barriers to entry and easy financing readily available (Lazonick, 1983). There have been large numbers of spinning firms and of new entrants in boom years, such as 1907. The industry conditions thus corresponded closely with the free entry assumptions of our model.

To apply the model and determine the price threshold, it is necessary to estimate five parameters: the trend and variance of the price process, $\alpha$ and $\sigma^2$ , the discount rate, *r*, the operating costs (relative to investment costs), *c*, and the incremental rate of productivity improvement for the new technology, $\mu$. The operating costs facing a mule spinner in this era can be obtained from Winterbottom (1907, p. 231) and are shown in Table 3.[9] Lazonick (1981) provides adjustments to these estimates to calculate the costs for ring spinning for warp yarn or yarn produced in an integrated spinning and weaving mill.

The relevant price series here 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

[8] 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). An equivalent calculation also applies to the production of weft yarn in an integrated spinning and weaving mill.

[9] Winterbottom (1907) used a depreciation rate of 4% as noted above. This has been replaced here with a depreciation rate of 2% that is closer to the actual retirement rate.

waste.[10] Our 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 somewhat to understate the true variance. 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, we use an estimate that is 10% greater, $\hat{\sigma}^2 = .035$.

Any long-run increases in price, of course, 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 is .000; the growth rate in cotton consumption (a measure of capacity) is .009 . Therefore $.000 + .009 = \hat{\alpha} - \tfrac{1}{2}\hat{\sigma}^2$, yielding $\hat{\alpha} = .0265$.

The appropriate risk-adjusted interest rate was 5% by all historical accounts, hence $r = .05$.[11] From Table 3, annual capital costs per pound of ring warp yarn were .27d ("d" denotes pence), 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.

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[10] 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 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 at 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 reasonably close (Daniels and Jewkes, 1928).

[11] This is the risk-free interest rate plus an adjustment for non-diversifiable risk as per the Capital Asset Pricing Model. This model is assumed to apply. There was an active trade in shares of spinning firms, including some unique financial instruments that allowed even small spinners to obtain equity financing (Lazonick, 1983).

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.[12] 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 rate of sustained productivity growth ($\mu$) of about 2% per annum.[13] 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 the productivity of spinning especially in integrated weaving and spinning firms.

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 $t = 0$, $\bar{q}$ , 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 is 25% higher than the entry threshold applicable 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) is 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.

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 1905 and (2) in 1908. If parity had been

[12] 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 (1984) actually find declining labor productivity from 1900 to 1913.

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

achieved in 1905, the spinner would have purchased rings in 1907 and again in 1913 and 1915. But if parity had not been achieved until 1908, the spinner would have purchased mules in 1907 and might not have purchased rings until 1917, a full ten years later.[14] 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 1905–7, 1912–13, and 1915. Thus the transition to the new technology would have decreased the frequency of investment overall.

Slight differences in cost can obviously generate large differences in the timing of adoption. Here, 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. The real options model provides a sharply different decision rule for investment in new technology than common rules based on accelerated depreciation.

It is 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% .[15] This hurdle rate includes the effects of uncertainty, obsolescence and the decrease in prices. By comparison, the return on capital investment in mules necessary to generate a price threshold of $p_0$ is only 17%. This latter hurdle rate exceeds the 5% risk-adjusted interest rate basically because of the effects of uncertainty. Nevertheless, there is no clear relationship between the difference among these hurdle rates and observed retirement rates. Any effort to infer a depreciation rate from observed equipment lives is not well founded. Assumed depreciation rates of around 10% are likely to fall far short of the appropriate hurdle rate implied by the real options model.

## 5 CONCLUSIONS

Standard analysis says, "buy the better mousetrap." Yet there are clear risks to such a policy when mousetraps continue to improve and when competitors may equip themselves better. No firm wants to be saddled with equipment that is soon to be obsolete. Conversely, faced with this reluctance, "building a better mousetrap" is not a sufficient business plan. Too many firms have built better mousetraps, yet the world failed to beat paths to their doors, at least not very quickly.

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[14] The chart only displays up to the year 1915 because the following years were marked by a sharp inflation and because equipment supplies were constrained by war production. The model does not incorporate inflation.

[15] That is, operating costs excluding capital costs are 1.22d/lb. so gross profits are 2.81 – 1.22 = 1.59d/lb. This is the return on 5.40d capital per pound.

This "conservatism" and the slow pace of technological adoption can be better understood in terms of a real options model. As suggested in this paper, the option value to waiting can be substantial even when the rate of incremental improvement in technology is small. The appropriate hurdle rate for investment can be substantially elevated for many years.

Managers sometimes use rules of thumb to compensate for anticipated obsolescence, e.g., they use accelerated depreciation rates. But such decision rules are rather arbitrary. Also, such rules cannot cope with technology transitions where there is an abrupt change in technology, as well as incremental improvement. Yet for some technologies such transitions are common. For example, computing has gone from mainframes, to mini-computers, to personal computers to the Internet, in just 40 years. Real options analysis provides better decision rules that can account for technology transitions, yet allow simple determination of investment thresholds and technological adoption policy.

## Appendix A

### Solution for Entry Threshold when New Technology is Superior

The first task is to solve for the entry threshold $\bar{p}(t)$ in the domain where $t$ is positive. Note that the value of a firm entering at time $t = v$ depends on expected price, expected equipment life ($T$), operating costs ($c \cdot e^{-\mu v}$), and equipment cost ($e^{-\mu v}$). The first two factors are independent of the entry time while the last two vary in proportion to $e^{-\mu v}$. Given the symmetry of the problem, the solution should take the form $\bar{p}(t) = \bar{q} \cdot e^{-\mu v}$ where $\bar{q}$ is a constant to be determined.

Given this symmetry, it is convenient to substitute variables:

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

where $0 \le \tau \le T$ and $q$ is a stochastic variable. After substitution, the partial differential equation with boundary conditions, (5), becomes

$$\begin{aligned} &\sigma^2/2 \ q^2 F_{qq} + \alpha q F_q - F_\tau - rF + q \cdot e^{-\mu(v+T-\tau)} - c \cdot e^{-\mu v} = 0 \\ &F(q,0) = 0, \qquad\qquad F(0,\tau) \text{ bounded} \\ &F(\bar{q},T) = e^{-\mu v}, \qquad\qquad F_q(\bar{q},T) = 0 \end{aligned} \tag{A1}$$

Note that the last two boundary conditions hold when $t = v$, or $\tau = T$.

Next it is helpful to take Laplace transforms of the equation and boundary conditions (see standard references on Laplace transforms such as Carrier and Pearson, 1968, or Riley, Hobson and Bence, 1997). Define the Laplace transform of $F$ with respect to $\tau$ as

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

It can be shown that $L[F_\tau(q, \tau)] = s \cdot \phi(q,s) - F(q, 0) = s \cdot \phi(q,s)$, the last equality from the boundary condition. Using other standard transforms, the transforms of the differential equation and boundary conditions are

$$\begin{aligned} &\tfrac{1}{2}\sigma^2 q^2 \phi_{qq} + \alpha q \phi_q - (r+s)\phi + \frac{q \cdot e^{-\mu(v+T)}}{s-\mu} - \frac{c \cdot e^{-\mu v}}{s} = 0 \\ &\phi(0) \text{ bounded} \\ &\phi(\bar{q}) = \frac{e^{-\mu v}}{s}, \quad \phi_q(\bar{q}) = 0, \qquad \text{for } \tau = T \end{aligned} \tag{A2}$$

where the argument $s$ has been suppressed in $\phi$ 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 ordinary differential equation 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 (A2). 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 $\tau$ is equated to $T$ after performing the inverse Laplace transform. Using these conditions to eliminate $A$ yields

$$\left(1 - \frac{1}{\beta}\right) \cdot \frac{\bar{q} e^{-\mu T}}{(r+s-\alpha)(s-\mu)} = \frac{1}{s} + \frac{c}{s(r+s)} . \tag{A3}$$

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 (A3) evaluated at $\tau = T$, gives

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

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 that $\bar{p}(t) = \bar{q} \cdot e^{-\mu t}$.

## Appendix B

### Entry Threshold when Old Technology is Superior

The price threshold appears to require a numerical solution in the domain $t < 0$. However, it is possible to calculate features of the solution and an approximation. First, note that the boundary conditions of (7) combined with (6) imply that $\bar{p}(0) = \bar{q}$.

Second, the left asymptote of $\bar{p}(t)$ can be determined. As $t \to -\infty$, any consideration of technology A becomes insignificant, so $U(p, t)$ must converge to $G(p)$ which obeys the equation

$$\tfrac{1}{2}\sigma^2 p^2 G_{pp} + \alpha p G_p - rG + p - c = 0 \qquad \text{(B1)}$$

and the equivalent boundary conditions. This ordinary differential equation solves to

$$\bar{p}(-\infty) = p_0 \equiv \frac{\beta}{\beta-1} \cdot (r-\alpha) \cdot \left(1+\frac{c}{r}\right), \qquad \beta \equiv \tfrac{1}{2} + \frac{-2\alpha + \sqrt{(2\alpha-\sigma^2)^2 + 8r\sigma^2}}{2\sigma^2}$$

where $p_0$ is the price threshold that would obtain if technology B were the only technology.

Finally, to approximate the behavior in between the left asymptote and the endpoint, $t = 0$, consider that when both $\alpha$ and $\sigma$ are small, then $U(p, t) \approx W(t)$ where $W$ is a solution to

$$W_t - r \cdot W + p - c = 0$$

and the corresponding boundary conditions. This solves to

$$W(t) = \frac{p-c}{r} \cdot \left(1 - e^{rt}\right) + V\left(p, 0; 0\right) \cdot e^{rt}, \qquad t < 0 .$$

Applying the free entry condition yields the price threshold for this case

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

Since $p_0 = r + c$ in this case, this can be generalized as a rough approximation,

$$\bar{p}(t) \approx p_0 \cdot \left(1 - e^{rt}\right) + \bar{q} \cdot e^{rt}, \qquad t < 0 .$$

Although this approximation is crude, our primary interest is in the domain $t > 0$.

## ACKNOWLEDGMENTS

I thank Avinash Dixit, Michael Gort, Lenos Trigeorgis, and an anonymous referee for helpful comments.

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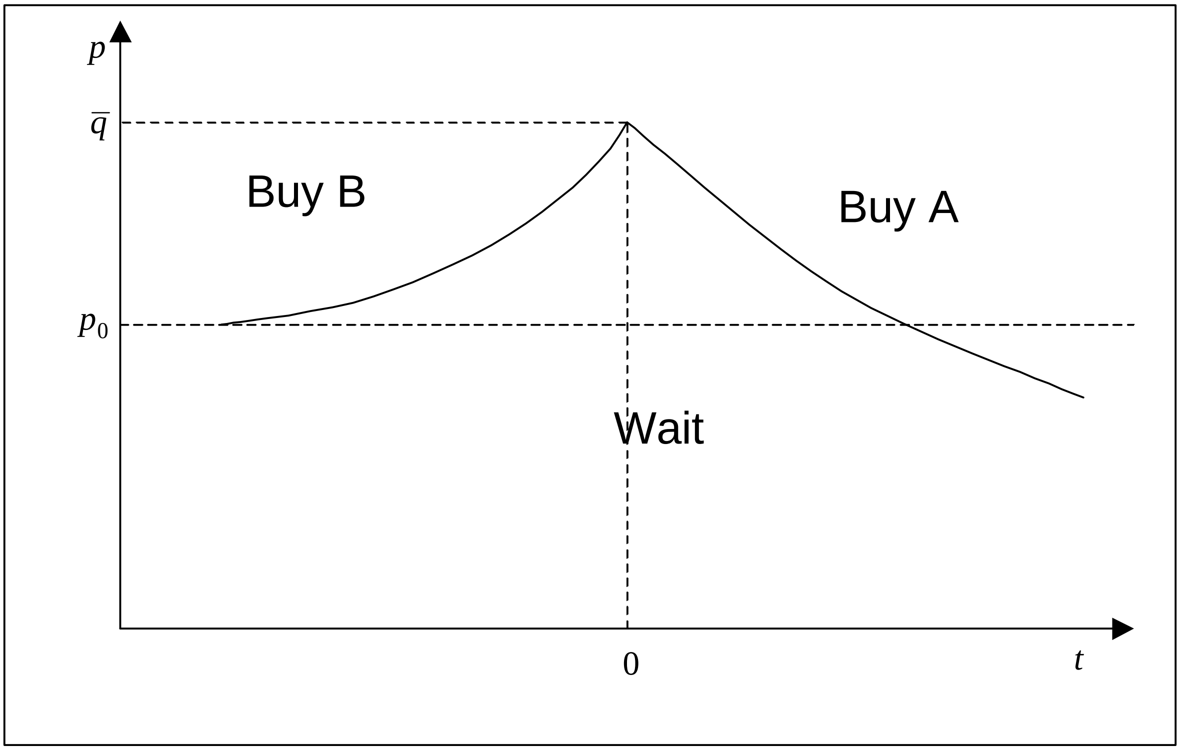


**Figure 1** Price entry threshold for industry with free entry for the old technology (B) and the new technology (A)—At time 0 technology A becomes more productive than B. Asymptote $p_0$ represents the entry threshold if B were the only technology.

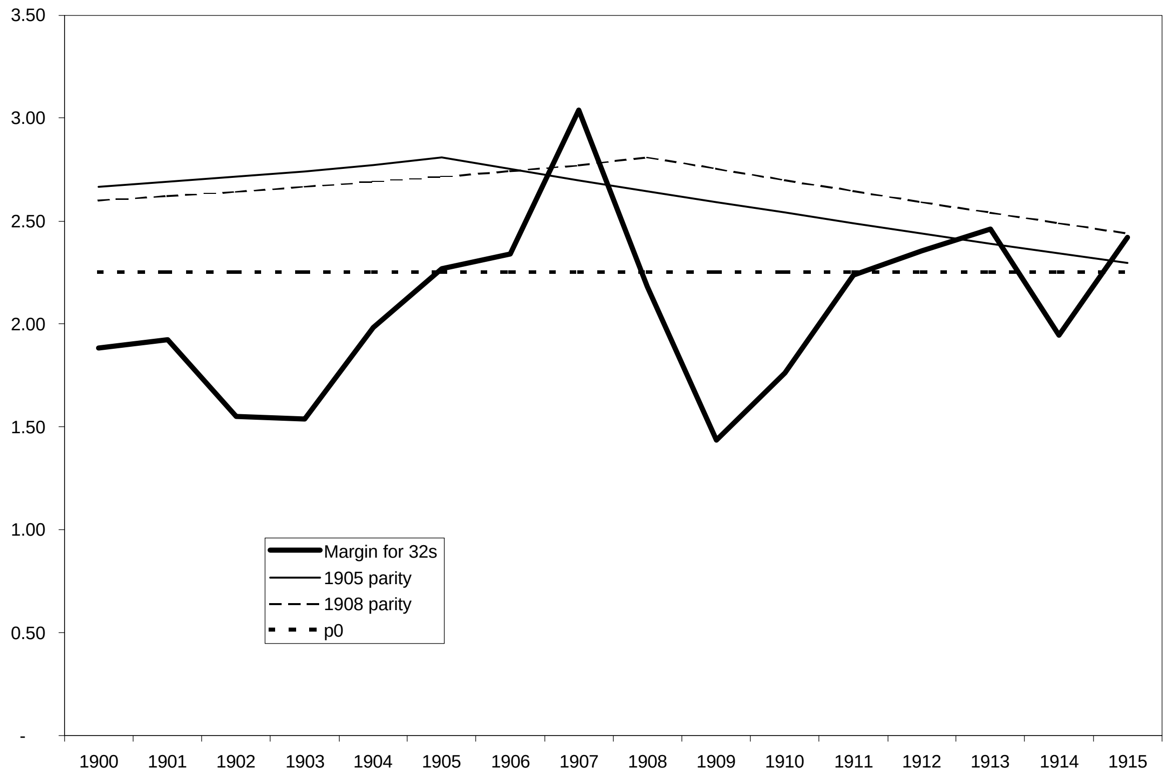


**Figure 2** Actual margin for 32s yarn in pence/lb. and calculated entry thresholds—Price thresholds are shown under alternate assumptions that ring spinning achieved parity with mule spinning in 1905 and in 1908. $p_0$ is the threshold under an assumption that ring spinning would never achieve parity.

Source: Margin data from Robson (1957) with adjustments for waste and selling expense from Winterbottom (1907). The years after 1915 experienced rapid war-related inflation and equipment supply constraints and have been omitted from the figure.

**Table 1** Threshold Parameters and Mean Durations for Industry with Free Entry[a]

| Discount rate $r$ | Price trend growth rate $\alpha$ | Productivity growth rate (tech. A) $\mu$ | $\bar{q}$ | 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 |

[a] Parameters: $\sigma^2$ = .04, $c$ = .05. $r$ is the discount rate adjusted for non-diversifiable risk (Capital Asset Pricing Model); $\alpha$ is the trend of the geometric price process below the threshold; $\bar{q}$ is the price entry threshold at time zero; $p_0$ is the price threshold had there been no new technology; $D(p_0)$ is the mean period (in years) 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[a]

| Discount rate $r$ | Price trend variance $\sigma^2$ | 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 |

[a] Parameters: $\mu = .03$, $\alpha = .03$. $r$ is the discount rate adjusted for non-diversifiable risk (Capital Asset Pricing Model); $\sigma^2$ is the variance of the geometric price process below the threshold; $c$ is operating costs relative to equipment price; $\bar{q}$ is the price entry threshold at time zero; $p_0$ is the price threshold had there been no new technology; $D(p_0)$ is the mean period (in years) 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 3** Typical Costs for Spinning Medium Yarn in Southeast Lancashire circa 1905 Excluding Base Cotton Cost, Cotton Waste and Selling Discount/Expense[a]

| **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** |

[a] 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 a price premium of about 0.25d (Sandberg, 1974), although this would fluctuate depending on market conditions. This premium tended to average about 5% historically, despite major changes in production of longer staple cotton (USDA). This calculation assumes that ring spinners would use 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.