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THE LIFE-CYCLE OF A COMPETITIVE INDUSTRY

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Abstract

Firm numbers first rise, and then fall as the typical industry evolves. This nonmonotonicity in the number of producers is explained in this paper using a competitive model in which innovation opportunities induce firms to enter, but in which a firm's failure to implement new technology causes it to exit.

The model is estimated with data from the U.S. Automobile Tire Industry, a particularly dramatic example of the nonmonotonicity in firm numbers: A big shakeout took place during the 1920s. The number of automobiles sold in the U.S. does not appear to explain this shakeout. Instead, the data point to the invention of the Banbury mixer in 1916 as the event that caused the big exit wave. There were, of course, other major inventions in the tire industry, but none seems to have raised the optimal scale of its adopters by enough to cause further shakeouts.

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Why is the number of producers nonmonotonic over an industry's life-cycle? The stylized facts of industry dynamics, familiar from studies of industry evolution by Gort and Klepper (1982) and Klepper and Graddy(1990), are the following: A young industry is populated by a few small firms, and the product commands a high price. Entry then expands the number of firms and each produces more, the combined effect being to raise output dramatically and lower price. Output growth persists, but the rate of growth falls below the growth rate of average firm size so that firms must exit– a "shakeout". The non-monotonic time path of firm numbers is the focus of this paper.

Figure 1 displays a striking example of this phenomenon– the U.S. Automobile and Tire Industry, 1906-1973. With just 10 firms producing in 1906, the number ballooned to 275 in 1922, and then– even before the onset of the Depression– receded to just 132 (in 1928). Later, firm numbers gradually drifted downwards, reaching about 30 by the end of the sample.

Data on the value of firms in the tire industry suggest that the industry became attractive indeed. Figure 1 also includes an index of the share prices of publicly traded firms in the tire and rubber industry, relative to an index of all share prices (Cowles,1939). (The figure is normalized so that the two indices were equal at the start of the sample period, 1906.) The period of increasingly rapid entry was preceded by sharply rising relative firm values, and the exit period was accompanied by an even sharper drop in relative firm values.

A candidate explanation for the time path of firm numbers is that it reflects the temporal behavior of the demand for automobile tires. Figure 1 also includes data on the annual sales of automobiles in the U.S. A pure demand side explanation would require firms to anticipate and exit in response to the onset of the Great Depression 7-8 years before its arrival, and then later, not to enter as demand steadily grew. The shakeout the tire industry experienced during the 1920's is not easily explained by variation in the demand for tires.[1]

The explanation advanced here is suggested by the data in Figure 2 on total output of automobile tires and an index of their prices. To accommodate the data in both Figures– especially firm numbers, total output and price– equilibrium must imply a declining product price, increasing average and total output, and a non-monotone time path for firm numbers. A Viner-type model of U-shaped average cost curves coupled with secularly growing demand implies rising industry output, but also growing firm numbers and a constant (or worse, increasing) product price. A model in which costs decline for some reason is needed to reconcile rising average and total output with declining price.

Theories of cost reduction are common. Flaherty (1980) and Jovanovic and MacDonald (1991) model decreasing costs as the outcome of costly attempts to increase production efficiency. Jovanovic (1982) models selection effects that can also lead to lower industry costs as high cost firms are weeded out. Spence (1981) and Jovanovic and Lach (1989) model learning-by-doing at the industry level that has the same effect. What all these models do not imply, however, is explosive growth of output and decline of the product price alongside rapid entry and subsequent exit. This paper develops and estimates a model that does this; the model also implies a time path for share values that mimics the features of the stock price data.

The model builds on the intuition offered by Gort and Klepper when trying to rationalize the seemingly ubiquitous shakeout phase in the forty six industries they analyzed. They argued that just preceding the shakeout there will be a "rise in innovation [that] ... not only reinforces the barriers to entry but, in addition, compresses the profit margins of the less efficient producers who are unable to imitate the leaders from among the existing firms. Consequently, the exit rate rises

[1] Jovanovic and MacDonald (1992) establish this conclusion more formally.

sharply until the less efficient firms are forced out of the market" (p. 634).

In this paper the rise in innovation that precipitates the shakeout is a response to an invention developed outside the industry in question. Once this invention has arrived, firms try to implement it. The winners of the implementation race stay in the industry and increase their output. Technological laggards exit, just as Gort and Klepper thought they would.

The model supposes the industry to have been spawned by a basic invention, and the shakeout to have been the result of a single major refinement. This is a strong assumption, but it is motivated by the stylized facts mentioned earlier. Technological improvement must have reduced production costs, but to have caused a shakeout, it must also have greatly increased the firm's optimal scale so that firm numbers had to shrink over time. Since a single shakeout is typical in the Gort-Klepper data, and striking in the tire industry in particular, the model posits just one improvement– the refinement. The tire industry data point to the invention, in 1916, of the Banbury mixer as this event. There were, of course, other major inventions in the tire industry, but none seems to have raised the optimal scale of its adopters by enough to cause further shakeouts. For simplicity then, the model abstracts from all but one refinement; even so, it fits the data surprisingly well.

The model's parameters are estimated from the data on firm numbers, industry output and tire prices displayed above. The following conclusions emerge. First, the impact of industry-specific innovation on costs dwarfs the impact of general improvement in factor quality. Second, technology that was "cutting edge" during the early phase of the industry's development stayed current for somewhat less than a decade. Third, since the price of the product was so high early on, early participants in the industry are estimated to have earned substantial rents. So did those who succeeded in implementing technology based on the refinement; there the source of the rents is lower production costs. But implementing the new technology was apparently not easy: the estimated probabilities of successful innovation are small.

1 Theory

Schumpeter distinguished between "invention"– the discovery of something new– and "innovation"– putting what has been learned to work commercially. In the spirit of his work, the model takes inventions to be exogenous events in science or other industries. Most such occurrences have no relevance for a particular industry, but once in a while an invention is especially useful, and the opportunity to profit through innovation presents itself. Incumbents may find this opportunity attractive, but others might as well, and entry may be the result. The model generates entry in exactly this way. As for exit, it is assumed that innovative success is stochastic, so that some firms succeed before others. Since innovation lowers marginal production cost, as firms innovate, industry output rises and the product price falls to clear the market. Naturally, this makes the industry less attractive to those incumbents who have yet to innovate. Eventually, they prefer to seek their fortunes elsewhere– they exit. In sum, innovation possibilities fuel entry, and failure to innovate prompts exit.

1.1 Basics

The model is cast in discrete time and has an infinite horizon. At each date t, there is a competitive market for a homogeneous good. Product market equilibrium generates a time path for the product price (p_t) and industry output (Q_t), and the entry and exit decisions of firms yield a time path for the total number of producing firms (f_t). These time paths are the theoretical counterparts to the data studied below.

How does the product market evolve? At each t, the behavior of consumers generates market demand, represented by the continuous and strictly declining *inverse* market demand,$D(Q)$,which does not vary over time. Thus, consumer learning about the product is suppressed, as are other potential sources of demand shift such as the introduction of complementary or competing goods, income growth, and so on. Specifying demand this way simplifies and makes it possible to ask if the industry life cycle can be understood primarily in terms of supply side considerations like technological change.[2]

1.2 Firms

There is a continuum of firms with total mass fixed at unity. A firm maximizes the expected present discounted value of its profits; the discount factor is $\gamma\,(0 < \gamma < 1)$.

At each t the firm decides whether to stay in the industry or go elsewhere. Leaving yields a profit flow of π^a. Staying yields an immediate return that depends on the product price along with its output and current know how.

A firm's know how can be in one of three states. The first is a primitive state in which the firm cannot produce in the industry at all, and thus earns a net revenue of zero by participating there; all firms are endowed with this know how. This state formalizes the idea that the industry cannot get started until some production process is available. The other two knowledge states are "low tech" and "high tech," represented by superscripts "l" and "h" respectively. Those states describe whether a firm has learned to put a certain invention to use commercially– i.e. whether it has innovated.

[2] Constant exogenous "general productivity growth" that effects the productivity of all factors of production, (and hence demand, via income growth) is admitted in the empirical work that follows. Without this addition, some elements of industry dynamics may be erroneously attributed to activities in the industry when they are in fact a consequence of growth in the economy at large.

1.3 Invention and Innovation

1.3.1 Invention

At the outset, only primitive know how exists, and all firms can access it. Since the primitive technology does not allow production, the commodity market does not operate. Subsequently, an initial "basic" invention arrives. This invention might be a fundamental chemical discovery such as plastics, or a technological breakthrough like the transistor, cathode ray tube, or steam engine, or even a mathematical advance like Shannon's Redundancy Theorem, which plays an important role in modern telecommunications. In any case, the basic invention offers the first possibility for commercial application– i.e. low tech innovation– leading to the opening of the product market at $t = 1$.

The model allows for one further invention, referred to as the "refinement". The hazard for this refinement is ρ. Innovations based on the refinement are high tech.

1.3.2 Innovation

Once the invention process has provided the raw material, firms may innovate. Innovation is a random event that can occur only for firms participating in the industry. At date t, if only the basic invention has arrived, a firm that has not previously innovated can do so with probability β. All such innovations are low tech, since they rely on the basic invention, and may be put to use in the following period. No further innovation is possible until the basic invention is refined. At that time participating firms who previously introduced low tech innovations may innovate again, doing so with probability r in any period, and putting what they have learned to use one period later. These innovations make use of the refinement and are thus high tech. Firms that have not succeeded in low tech innovation (including any new entrants) may also innovate, and, in general, might introduce either low or high tech innovations. For simplicity, also because it is descriptive of the data analyzed below, it will be assumed that these firms can only introduce low tech innovations, the probability of this outcome being r^{ϕ}.[3]

Thus, if only the basic invention has occurred, a participating firm develops a low tech innovation with probability β, while if the basic invention has been refined, participating firms that already know how to use the basic invention innovate again with probability r, while new entrants introduce low tech innovations with probability r^{ϕ}.

Pulling all this together, innovation is bounded by invention. If primitive know how is all that exists, the industry does not function and all firms operate elsewhere; this phase of industry evolution precedes $t = 0$ and will be ignored in what follows. Once the basic invention has occurred, which defines $t = 0$, firms may enter the industry, and each participant faces a constant per period probability β of low tech innovation. The basic invention may then be refined from outside the industry, with a probability of refinement of ρ per period. After the refinement, low tech participants face a constant per period probability r of high tech innovation. New entrants, or those who failed to innovate earlier, acquire low tech know how with probability r^{ϕ} per period.

1.4 Optimal Behavior for Firms

Each firm must decide whether to participate in the industry or elsewhere. The value of these alternatives depends on the firms present know-how, the product price (summarizing the impact of others' know-how on the firm) and whether the refinement has arrived.

Innovation changes the firm's know-how and thus alters the profitability of participation in the

[3] The working paper version (Jovanovic and MacDonald, 1992) contains the theory and data analysis in the absence of this constraint. The theory is only marginally altered, and the data analysis is identical, the latter occurring because the correspondence between data and theory could always be improved by reducing the probability that a new entrant might introduce a high tech innovation.

industry. That is, by participating in the industry, a low tech firm– i.e. one whose knowledge state is l– earns $\pi^l(p)$ when the product price is p, where $\pi^l(p)$ is a standard profit function; likewise a high tech firm earns $\pi^h(p)$. Assume that for all positive p: $(i)\, 0 < \pi^l < \pi^h$, and $(ii)\, 0 < q^l(p) < q^h(p)$, where $q^l(= \partial\pi^l/\partial p)$ and $q^h(= \partial\pi^h/\partial p)$ are the supply curves for low and high tech firms.

Let U_t^ϕ be the maximum value of the firm at t, given only primitive know-how and assuming the refinement has yet to arrive; let V_t^ϕ represent the same thing, but, instead, *given* the refinement. Define the value functions U_t^l and $V_t^l\,(V_t^h)$ analogously, but given a low (high) tech state of knowledge for the firm. Then, before the refinement, optimal firm behavior implies:

$$U_t^\phi = \max\left\{\begin{array}{c} \pi^a + \gamma[\rho V_{t+1}^\phi + (1-\rho)U_{t+1}^\phi], \\ \gamma\left\{\rho[\beta V_{t+1}^l + (1-\beta)V_{t+1}^\phi] + (1-\rho)[\beta U_{t+1}^l + (1-\beta)U_{t+1}^\phi]\right\} \end{array}\right\}, \tag{1}$$

$$U_t^l = \max\{\pi^a, \pi_t^l\} + \gamma[\rho V_{t+1}^l + (1-\rho)U_{t+1}^l]. \tag{2}$$

After the refinement, on the other hand, optimal behavior implies

$$V_t^\phi = \max\left\{\pi^a + \gamma V_{t+1}^\phi, \gamma[r^\phi V_{t+1}^l + (1-r^\phi)V_{t+1}^\phi]\right\}, \tag{3}$$

$$V_t^l = \max\left\{\pi^a + \gamma V_{t+1}^l, \pi_t^l + \gamma[r V_{t+1}^h + (1-r)V_{t+1}^l]\right\}, \tag{4}$$

and

$$V_t^h = \max\{\pi^a, \pi_t^h\} + \gamma V_{t+1}^h. \tag{5}$$

Equations (1)-(5) say the following. In (1), the firm has primitive know how and only low tech innovation is feasible. In this case the value of the firm is larger of the returns to two options.

The first is to produce elsewhere at t. This yields π immediately, plus the discounted value of the firm one period later with no greater know how; this future value depends on whether the refinement occurs at $t+1$. The second option involves the firm entering the industry at t, hence earning no revenue at all during that period given its primitive state of knowledge, but generating the discounted value of the firm one period later; this future value depends both on whether the refinement occurs at $t+1$ and whether the firm innovates at t. Equations (2)-(5) have analogous interpretations.

1.5 Equilibrium

Two conditions must be satisfied: (i) firms choose maximizing actions at each t given their own state of knowledge and whether the refinement has come on the scene; and (ii) given firm actions, p_t is such that the product market clears at all t.

1.5.1 Intuition

A group of firms, endowed with primitive know how, enters the industry when the basic invention occurs. A fraction β of these firms innovate, thereby becoming low tech firms, and begin production at $t = 1$; the rest fail and go elsewhere.[4] Nothing further happens until the refinement arrives. That is, the product market is a static demand and supply setup with demand as above and supply coming from the existing low tech firms, and this market has an unique equilibrium price and quantity at each date. When the refinement arrives, low tech firms continue to produce and an additional group of firms may enter in hopes of innovating. Since the entrants have only primitive know how, they do not produce during the period in which the refinement arrives, in which case the observed values of price, quantity and number of producing firms do not change until the next

[4] It is possible that not all firms that innovate at $t = 0$ wish to produce before the refinement date; this is ignored in the present discussion, but accounted for in the formal analysis below.

period. In the next period a fraction r of the low tech firms has become high tech, and of the new entrants, a fraction r^{ϕ} has become low tech. The rest of the entrants failed to learn and exit. Thus, at this point the industry comprises a mixture of low and high tech firms. As time passes and more low tech firms innovate, thus becoming high tech, the blend of firms in the industry is increasingly high tech. At this point the assumption that high tech firms produce more plays its role. As high tech grows as a fraction of producing firms, industry output must rise and price must fall. There are two possibilities for the remainder of the market's evolution. In one, parameters are such that even if almost all firms have become high tech, the remaining low tech firms do not find exit attractive. In this case there is never any exit. Otherwise, as the product price continues to fall, there comes a point at which exit must occur. This exit can take two forms. If high tech firms are much bigger than low tech firms, or low tech firms become high tech easily, industry output grows quickly, and thus price falls quickly. In this case exit is "catastrophic": low tech firm exit en mass. In the opposite case output rises more slowly and exit is gradual, in fact maintaining a constant product price over time; that is, the industry output lost through exit of low tech producers is just sufficient to offset the increase in output enjoyed by innovators.

In brief, equilibrium implies the following observed features of the industry life-cycle: price is highest at the outset, falling only after the refinement, with its decline ceasing either gradually, if there is no exit, or more abruptly, if there is exit. The time path of industry output is simply that which makes this price path consistent with demand for the product. The number of participating firms rises at first, remains steady until the refinement, and then (typically) increases further. Firm numbers either stabilize at that point or fall through exit, which may be rapid or gradual.

The evolutions documented by Gort and Klepper are more gradual than those implied by equilibrium in this model, but they share gross features. That is, both have output rising and price falling, with firm numbers firm rising and later either stabilizing or dropping off.

1.5.2 Formal Analysis

Throughout, trivial cases are avoided by assuming D to be arbitrarily large (small) for small (large) p.

Let the mass of firms in the three states at date t be $N_t \equiv (N_t^\phi, N_t^l, N_t^h)$, and $n_t \equiv (n_t^\phi, n_t^l, n_t^h)$ be the mass of *participating* firms; note $f_t \equiv n_t^l + n_t^h$.

The evolution of n_t falls into four epochs: (i) the date of the basic invention, normalized to $t = 0$; (ii) any periods after the basic invention but preceding the refinement, $0 < t < T$; (iii) the refinement date, T; and (iv) all periods following the refinement, $t \geq T + 1$.

Epoch $t \geq T+1$. Assume the refinement occurred last period, and that only low and high tech firms are participating: $n_{T+1}^\phi = 0, n_{T+1}^l \geq 0$ and $n_{T+1}^h > 0$.[5] Three different evolutions are possible. To determine what they are, let p^* uniquely solve

$$\frac{\pi^a}{(1-\gamma)} = \pi^l(p^*) + \frac{\gamma}{(1-\gamma)}[r\pi^h(p^*) + (1-r)\pi^a], \tag{6}$$

and n^{h*} uniquely solve

$$p^* = D[n^{h*}q^h(p^*)]. \tag{7}$$

If $p_t = p^*$ for all t, a low tech firm is indifferent between participation and exit; n^{h*} is the mass of high tech firms that would, as a group, produce output consistent with $p_t = p^*$.

If, $f_{T+l} \leq n^{h*}$, there are so few firms that even if all other firms obtained high tech know how, the product price would remain so high that no low tech firm would ever want to exit. In this case

[5] Below it will be verified that either low or high tech know how is required for participation at $t \geq T+1$ – in particular, no firm having only primitive know how would ever find it advantageous to enter–and that the mass of high tech firms must be strictly positive for all such t.

the mass of producing firms, f_{T+1}, would remain constant but its composition would shift towards high tech firms according to

$$n^l_{t+1} = (1-r)n^l_t$$

and

$$n^h_{t+1} = n^h_t + rn^l_t.$$

If, instead, $f_{T+1} > n^{h*}$, exit must occur eventually because gradual innovation will raise industry output and lower the product price below p^* forever, implying the remaining low tech firms would want to exit.

There are two possible kinds exit patterns. The first emerges if innovation does not cause industry output to rise too rapidly, so that the condition

$$q^l(p^*) > rq^h(p^*) \tag{8}$$

holds. Let $T' \geq T+1$ be the first date for which, if no firm exited, $p_t < p^*$. For $t \geq T'$, let exit x_t by low tech firms be sufficient to hold $p_t = p^*$ as the market clearing price. Condition (8) guarantees that this can be done at each t without exit by all low tech firms.

Between $T+1$ and $T'-1$, p_t falls and there is no exit. And given the definition of p^*, the exit path sustaining $p_t = p^*$ for $t \geq T'$ is equilibrium behavior. The implied evolution of n^l_t (for $t \geq T+1$) is given by

$$n^l_{t+1} = (1-r)n^l_t - x_{t+1},$$

where $x_t = 0$ for $t < T'$, and for $t \geq T'$, x_t is such that output is exactly sufficient to cause the product market to clear at price p^*:

$$(n^h_{t-1} + rn^l_{t-1})q^h(p^*) + [(1-r)n^l_{t-1} - x_t]q^l(p^*) = n^{h*}q^h(p^*).$$

The evolution of n_t^h is then, for $t \geq T+1$,

$$n_{t+1}^h = n_t^h + rn_t^l,$$

where $n_{T+1}^h = rn_T^l$.

When (8) fails, the departure of all low tech firms at T' is not enough to maintain $p_t = p^*$. In this case, all low tech firms exit at T', and p_t then remains constant at some value below p^*. Moreover, for some parameter values and values of n_T^l and n_T^h, some low tech firms will also exit at $T'-1$. This possibility arises because given that all remaining low tech firms will exit at T', the product price will be constant and strictly less than p^* for all $t \geq T'$. In this case the value of obtaining high tech know at date $T'-1$ is less than it would be if price were to equal p^* in the future. This may cause the value of participation by low tech firms at $T'-1$ to fall short of the value of exit unless the product price is supported by some departure of low tech firms at $T'-1$. In this case, $n_{T'-1}$, $x_{T'-1}$, $p_{T'-1}$ and $p_{T'}$ solve

$$\frac{\pi^a}{(1-\gamma)} = \pi^l(p_{T'-1}) + \gamma\left[r\frac{\pi^h(p_{T'})}{(1-\gamma)} + (1-r)\frac{\pi^a}{(1-\gamma)}\right],$$

$$p_{T'-1} = D\left[n_{T'-1}^h q^h(p_{T'-1}) + n_{T'-1}^l q^l(p_{T'-1})\right],$$

$$p_{T'} = D\left[\left(n_{T'-1}^h + rn_{T'-1}^l\right) q^h(p_{T'})\right],$$

and

$$n_{T'-1}^l = (1-r)n_{T'-2}^l - x_{T'-1}.$$

In sum, for the final epoch ($t \geq T+1$), either the total number of operating firms remains constant forever, or exit begins at some point. Without exit, the product price drifts downward endlessly and industry output continually grows. If there is exit, it is either gradual or catastrophic.

In either case price falls and output grows before exit begins, but in the gradual exit case the departure of low tech firms maintains a constant product price and industry output as soon as exit has begun. Catastrophic exit also implies that price and output cease to evolve, but they may do so the period following the onset of exit.[6]

Epoch $t = T$. As will be verified below, all low tech firms participate at T; i.e. $n_T^l = N_T^l$. The only other issue that is relevant at date T is the extent of entry.

Given a mass of new entrants n_T^ϕ at T, innovation implies $n_{T+1}^l = (1-r)n_T^l + r^\phi n_T^\phi$ and $n_{T+1}^h = rn_T^l$. Given these expressions, the evolutions set out above for $t \geq T+1$ can be employed to calculate the price path over that period, and hence to calculate the expected present discounted value of profits earned through entry. It then follows that in equilibrium the mass of new entrants at T is either 0 or whatever positive number suffices to reduce the expected present value of the entry option to $\pi^a/(1-\gamma)$.

Epoch $1 \leq t < T$. Suppose $n_0^\phi > 0$ firms with basic know-how entered at $t = 0$. Then, the mass of firms with low tech know how at $t = 1$ is $N_1^l = \beta n_0^\phi$; there are no high tech firms at this point. Also, there will be no more entry until the refinement. If a positive measure of firms did enter between periods 1 and T, each would face the same prospects as did period 0 entrants, with one exception: such entrants would face more competitors than did period 0 entrants, and therefore be strictly worse off than period 0 entrants were when they entered. Therefore, n_t^l and N_t^l will be constant until T. Whether the constraint $n_t^l \leq N_t^l$ holds as an equality depends on whether $\pi^l(p_t)$ exceeds

[6] All three possible exit paths (none, gradual and catastrophic) appear to be relevant empirically. For example, in the Gort and Klepper data, among industries that appear to have reached "maturity" by 1973, little or no exit has occurred in the baseboard radiant heater, electrocardiograph and florescent lamp industries. Gradual exit appears to be the rule for producers of electric blankets, streptomycin and cathode ray tubes. Very rapid exit characterizes the electric shaver, automobile tire and penicillin industries.

π^a. If it does, then $n_t^l = N_t^l$ is equilibrium behavior. Otherwise, equilibrium demands participation only by a mass of firms sufficient to cause $\pi^l(p_t) = \pi^a$.

Epoch $t = 0$. Equilibrium requires that n_0^ϕ be sufficient to equate the value of entry with $\pi^a/(1-\gamma)$[7].

Briefly then, the equilibrium evolution of the distribution of firms is as follows. As soon as the basic invention arrives, a positive mass of firms with primitive know how enters; each expects a payoff equal to the value of participating elsewhere. Some of these firms succeed in acquiring low tech know how. Those that fail depart immediately (never having produced). There is no further entry until the refinement date, at which time positive entry may occur; any entrants again expect a payoff equal to the value of participation elsewhere. There will be no further entry and, like what occurs at the outset, any entrant that fails to innovate at the refinement date leaves the industry (again, never having produced). Firms participating in the industry after the refinement date gradually learn high tech know how, but those who are unlucky and remain low tech may begin to exit at some point. Depending on parameters, exit may be either gradual or catastrophic.

The equilibrium evolution of n_t implies time paths for both the product price and industry

[7] Along the way it was assumed that (*i*) all low tech firms would participate at the refinement date ($n_T^l = N_T^l$); (*ii*) following the refinement date there would be no entry by firms that have not innovated ($n_t^\phi = 0$, all $t \geq T+1$); (*iii*) a strictly positive mass of high tech firms must participate at all dates after the refinement date ($n_t^h = N_t^h > 0$, all $t \geq T+1$); and (*iv*) some firms would enter at the outset ($n_0^\phi > 0$). (*ii*) follows from the fact that the refinement date is the most advantageous time for such firms to enter. At any later date the product price will have fallen and the value of entry is strictly below that available by going elsewhere. As for (*i*), if some low tech firms were content to go elsewhere at the refinement date, the value of participation at that point is at most $\pi^a/(1-\gamma)$. In particular, the product price at that date can be no more that needed to yield $\pi^l(p_T) = \pi^a$, since one option low tech firms have is to participate at T and not later. It follows that low tech firms must exist in sufficient numbers to allow this equality to hold. But this implies that this equality must hold at all earlier dates too, since if $\pi^a(p_t) > \pi^a$ ever held, all low tech firms would wish to participate. Thus, the capital value of participation by a low tech firm can never exceed $\pi^a/(1-\gamma)$. However, this implies that no firm would ever give up π^a for one period to acquire low tech know how; that is, $N_t^h = 0$, all t. Since this implies industry output is 0, this outcome is inconsistent with the assumption that price is high when aggregate output is low. As for (*iii*), in equilibrium there must be some high tech firms participating at $T+1$, for otherwise no low tech firm would wish to participate either, and the product market would not clear at $T+1$. Also, since the value of participation by a low tech firm is both strictly less than that of a high tech firm and no less than $\pi^a/(1-\gamma)$, no high tech firm would find it profitable to exit at any date. Finally, as for (*iv*), no entry at the outset is again inconsistent with what has been assumed about product demand.

output. These values are obtained by equating product demand and supply at each date, taking as given the mass of participating firms in each knowledge state. In particular, the product price is a constant prior to the refinement date, may drop at that date, depending on whether all low tech firms were participating prior to the refinement, and falls after that until exit begins, at which time price again remains constant over time.[8] The evolution of industry output is simply quantity demanded at each date given the price path just described.

2 Data

This section analyzes the U.S. Automobile Tire industry data in the context of the model set out above.

2.1 U.S. Automobile Tire Industry Data

The Tire Industry data were collected by Gort and Klepper. This industry was chosen because its data series is relatively long, and also because– in contrast to some other industries on which data area available– Rocket Engines, Computers– the definition of the commodity is relatively clear.

The data include number of producing firms (1906-73), industry output (1910-73) and a wholesale price index for automobile tires (1913-73). They are reported in the Appendix[9] .

Several points about the data deserve mention. First, the data enumerate firms rather than plants. If information flows smoothly within plants, the empirical counterpart of the number of producers in the model is firms, not plants.

Second, the data do not contain information on mergers. Based on the model, the data analysis

[8] Strictly, in the catastrophic exit case, the price does not become constant until the period in which all low tech firms depart; exit may begin one period before this.

[9] A few firms existed prior to 1906. The *Thomas Register of American Manufactures* gives 1906 as the earliest date at which positive output was observed; 1905 therefore corresponds to $t = 0$ in the theory. Also, while wholesale prices are presumably what drives the decisions of sellers, *retail* prices are relevant for buyers. Provided retail/wholesale markups are constant over time, the constant d_0 (in the parameterization used below) embodies the markup.

interprets a merger as an exit of one of the parties and survival of the other. This is appropriate if mergers in fact serve to allocate resources to more technologically advanced producers. It would be inappropriate if mergers were instead driven by, for example, the desire of equally advanced producers to pool resources for financial reasons.

Third, the life-cycle behavior that is the focus here had all but ended by 1940, so that the results are not likely to depend much on how allowance for the second world war is made. While price and number of producers were somewhat influenced by the war, industry output fell dramatically as production capacity was utilized for military production over 1942-5. The approach taken here replaced the 1942-45 output figures by a linear interpolation of the 1941 and 1946 figures. The Appendix reports both the adjusted and original numbers.

Finally, quality change. The theory assumes that the service flow obtained from a tire is constant. The tire price series was deflated by the CPI, which amounts to assuming that unmeasured quality increase in tires was the same as the unmeasured quality change in the CPI commodity bundle[10] .

2.2 Parameterization

Inverse demand has constant elasticity:

$$D(Q) = d_0 Q^{-d_1}.$$

Profits are of the form

$$\pi^h(p) = p^2(1+\theta)/2c \tag{9}$$

and

$$\pi^l(p) = p^2/2c. \tag{10}$$

[10]The latter has been argued to be substantial; see the papers in Griliches (1971).

These profit functions arise if low tech costs are $cq^2/2$ and high tech costs are $cq^2/2(1+\theta)$, where $1+\theta$ represents the factor by which costs are reduced when high tech is acquired.

Given parameter values, a time path for the model economy is obtained as follows. Fix the refinement date, and the mass of entrants at the outset and refinement dates (n_0^{ϕ} and n_T^{ϕ}). The description of equilibrium given above then implies a time path for n_t and a sequence of prices and industry outputs. This sequence follows from the equality of supply and demand at each date, given the time path for n_t. Indeed, under the assumed functional forms,

$$p_t = d_0^{1/(1+d_1)} \left(\frac{n_t^l + n_t^h(1+\theta)}{c} \right)^{-d_1/(1+d_1)}$$

and

$$Q_t = \left(\frac{p_t}{d_0} \right)^{-1/d_1},$$

where $n_t^h = 0$ prior to the period following the refinement date.[11]

To construct an *equilibrium* time path, all that remains is to determine values for n_0^{ϕ} and n_T^{ϕ} that, if possible, equate the value of entry for firms having only basic know-how to the value of participation elsewhere. To do so, expressions for the value of entry by firms having only basic know-how are needed. These expressions depend on the exit path. Take the case of positive entry at the refinement date, and no exit at any point. (The expressions for the other cases are similar.) The value of a high tech firm is the discounted value of its profits. Using (9), this is

$$V_t^h = \left(\frac{1+\theta}{2c} \right) \sum_{\tau=0}^{\infty} \gamma^{\tau} p_{t+\tau}^2. \tag{11}$$

Since there is no exit, the value of a low tech firm at $t \geq T$ is also the present value of profits from producing in the industry, taking into account that high tech know how might be acquired as

[11] These expressions assume $n_t^l = N_t^l$ for $0 < t < T$; analogous expressions when this is not the case are similar.

well. After simplification, this is (for $t \geq T$)

$$V_t^l = \frac{1}{2c}\left\{\sum_{\tau=0}^{\infty}\gamma^\tau p_{t+\tau}^2\left(1+\theta\left[1-(1-r)^\tau\right]\right)\right\}. \tag{12}$$

The value of entry to firms having only basic know how then is

$$V_T^\phi = \gamma\left[r^\phi V_{T+1}^l + (1-r^\phi)\frac{\pi^\alpha}{(1-\gamma)}\right] \tag{13}$$

Since participation yields no profit during the initial period, entry at $t=0$ offers the firm

$$U_0^\phi = \gamma\left\{\beta[\rho V_1^l + (1-\rho)U_1^l] + (1-\beta)\frac{\pi^a}{(1-\gamma)}\right\}. \tag{14}$$

This uses the fact that if the firm does not acquire low tech know how at $t=0$, its value at $t=1$ is simply the value of participation elsewhere. In (14), V_1^l is obtained from (12) by assuming $t=T=1$. Similarly, if the refinement has not occurred by $t=1$,

$$U_1^l = \pi^l(p_1) + \gamma[\rho V_2^l + (1-\rho)U_2^l].$$

Since $U_1^l = U_2^l$, this may be solved for U_1^l, using (12) for $t=2$.

In equilibrium, the values of n_0^ϕ and n_T^ϕ equate U_0^ϕ and V_T^ϕ to $\pi^a/(1-\gamma)$ if this is possible with positive n_T^ϕ, or else equate U_0^ϕ to this value and leave the value of entry at T strictly less. Given equilibrium values for n_0^ϕ and n_T^ϕ and a fixed refinement date, the evolution set out above determines a sequence $\{p_t, Q_t, f_t\}$, which can be compared to the data.

One parameterization issue remains. The U.S. economy is growing and productivity is improving generally. The model assumes the rest of the economy is unchanging. To allow for general economic growth in a parsimonious way, assume that quantity demanded can increase by the factor g each year without a change in price, and that, all else constant, profits π^a, π^l and π^h also rise by this factor; i.e. replace $D(Q)$ with $D(Q/g^t)$, and π^a, π^l and π^h with $\pi^a g^t, \pi^l g^t$ and $\pi^h g^t$. This "homogeneous growth" specification can be derived from a general equilibrium setup in which product demand is unit income elastic and the industry is small relative to the rest of the economy, with all production possibilities experiencing neutral technological change at annual rate $g - 1$.

If growth takes this form, then it is easy to verify that (i) the industry behaves just as described above, except for the replacement of γ by $\gamma' \equiv \gamma g$; and (ii) given γ', the time paths of firm numbers and price are independent of g and the output path is that associated with $g = 1$, scaled by g^t. With this addition, the model's parameters are $\rho, \beta, r, r^{\phi}, \gamma', g, \pi^a, d_0, d_1, c$ and θ

2.3 Comparing Theory and Data

Given parameter values *and refinement date* T, assume that the data differ from the theoretical time paths by random variables:

$$\ln p_t^* = \ln p_t(T) + \varepsilon_{p_t}, \tag{15}$$

$$\ln Q_t^* = \ln Q_t(T) + \varepsilon_{Q_t}, \tag{16}$$

and

$$\ln f_t^* = \ln f_t(T) + \varepsilon_{f_t}, \tag{17}$$

where the data are distinguished by asterisks, the dependence of the theoretical time paths on T is explicit, and the "error terms" are independent of each other and over time, with variances σ_p^2, σ_Q^2 and σ_f^2.

Equations (15)-(17) imply a likelihood function, *conditional on* T. Given that ρ is the hazard for the refinement, this conditioning can be removed to yield the likelihood function that is maximized by suitable choice of $\rho, \beta, r, r^{\phi}, \gamma', g, \pi^a, d_0, d_1, c$ and θ.[12]

[12]Let D_p, D_Q and D_f be the set of dates for which the data p^*, Q^* and f^* are observed, where $D_p \subset D_Q \subset D_f$, and T_p, T_Q and T_f the corresponding number of observations on each. Then the likelihood of the data given$T$ and the

2.4 Parameter Values and Discussion

Parameter values are in Table 1; Figure 3 repeats the data and superimposes the model's predicted time paths for price, quantity and firm numbers *assuming a refinement date of* 1913, the expected arrival date implied by $\rho = .125$.

Three general remarks: Annual productivity growth is estimated at $(100\times(g-1) =)$ 2.93%; for comparison, the annual growth rate of real GNP over the period was 3.11%. As Figure 3 shows, the primary role played by g is to allow industry output to display a trend beyond that arising from the temporal behavior of know-how. Second, the elasticity of demand is estimated at $(1/d_1=)$ .763– i.e. inelastic demand– which is consistent with the small fraction tires make up in the total cost of an automobile. And third, this highly stylized model matches the data quite well. This is evident from the Figure as well as from the high correlations of the predicted series with the actual: .88 for firm numbers, .96 for output and .72 for price.

The model indicates that the impact of innovation on production costs was huge, reducing them by a factor of $(1+\theta \approx)97$, far in excess of the seven-fold cost reduction that general productivity growth alone would have produced over the same period. Industry-specific technological change had to be very large in order to generate the kind of growth in firm size needed to accommodate both the high price and large number of firms near the refinement date, and the low price and

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parameters is

$$L(T) \equiv \frac{\exp - \left\{ \frac{1}{2\sigma_p^2} \sum_{t\in D_p} [\ln p_t^* - \ln p_t(T)]^2 + \frac{1}{2\sigma_Q^2} \sum_{t\in D_Q} [\ln Q_t^* - \ln Q_t(T)]^2 + \frac{1}{2\sigma_f^2} \sum_{t\in D_f} [\ln f_t^* - \ln f_t(T)]^2 \right\}}{\sqrt{(\sigma_p^2)^{T_p} (\sigma_Q^2)^{T_Q} (\sigma_f^2)^{T_f}}}.$$

The sample likelihood is then given by

$$L \equiv \sum_{T\in D_f} \rho(1-\rho)^{T-1} L(T) + (1-\rho)^{T_f} L(T_f + 1).$$

In the empirically relevant subset of the parameter space, not all parameters are identified; specifically, only two of β, γ' and π^a are identified. In all that follows it is assumed that $\gamma' = .925$. The identification issue is discussed fully in Jovanovic and MacDonald (1992, p. 24 and fn. 19).

small number of firms later. The influence of general productivity increase alone is much too small to generate the necessary growth in firm size.[13]

The refinement probability is .125, indicating that the expected time until refinement was eight years. Firms entering in 1905 in hopes of putting low tech know to work could, therefore, expect low tech methods to remain current until about 1914. According to the theory, the prospect of the technology available early on remaining current for a reasonably long period was one feature of the industry that attracted so many entrants. Indeed the configuration of demand and cost generated substantial rents for early innovators: relative to the value of a firm elsewhere, the value of a low tech firm was $U_t^l/\left(\frac{\pi^a}{1-\gamma'}\right) = 5.83$ prior to the refinement. The arrival of the refinement, implying a sharply declining price and a severe reduction in firm numbers, was bad news for existing low tech firms: $V_T^l/\left(\frac{\pi^a}{1-\gamma'}\right) = 2.87$.

Technological know-how generated substantial rents, as is evidenced by the values just mentioned, along with the even-greater returns to getting high tech know-how early: $V_{T+1}^h/\left(\frac{\pi^a}{1-\gamma'}\right) = 24.97$. According to the model, these rents were supported by extremely difficult innovation. New entrants faced a one in $(1/\beta \approx)$ sixty chance of implementing low tech early on, improving to only one in $(1/r^\phi \approx)$ nine after the arrival of the refinement. The odds of a low tech firm implementing high tech were just one in $(1/r \approx)$ fifty-two. Evidently, implementing cutting-edge technology– low or high tech– was a major accomplishment, and the rewards were correspondingly large.

Why were rents in the tire industry so large and innovation so difficult? For strong growth in industry output to continue in the face of dramatic exit, as occurred into the 1930's, the transition from low to high tech had to involve a significant expansion of the survivors' scale. Since the decline in the product price was gradual in comparison to the decline in firm numbers, this implied that

[13]The ratio of the average firm size for the last decade of the sample relative to the first (1910-1919, since output data begins in 1910) is 47.6.

rents to high tech know-how were large, and so equilibrium demands that these rents were hard to get. This explains why transiting from low to high tech was so difficult.

Why was it hard to get low tech at the outset? For there to be many new entrants at T, the stock of low tech incumbents could not have been too large at T; otherwise, the industry would have evolved too quickly for entry at T to be attractive. Thus, there must have been relatively few incumbents at T, which kept the product price high and generated substantial rents for these firms. Consequently, these rents had to be hard to obtain.

2.5 Other data

2.5.1 Stock Prices

The model has precise implications for the time path of firm values in the tire industry. Firm value (U_t^l) is large before T, then declines sharply at T ($U_t^l > V_T^l$) with firms that become high tech early being extremely valuable (V_{T+1}^h is large). But more can be said since explicit time paths for these values can be computed. How do these implications compare to stock price data?

If all tire firms were publicly traded, and all firms (tire manufacturers and others) had constant debt/equity ratios, possibly varying across industries, movements in relative stock prices would be proportional to firm values, and the model's implications for asset prices could be checked by comparing movements in market values of firms in the tire industry to movements in the value of firms elsewhere[14] .

The assumption that debt/equity ratios are constant cannot be checked directly for the period in question, but Holland and Myers(Table B-2a) report debt/equity ratios for U.S. corporations over the 1929-81 period. Debt/equity rose significantly during the great depression and did not return

[14]Here, stock price refers to share values *including dividends*- the "cum-dividend" price– so that any predictable variation in profits will be reflected in the price of the asset. For example, an asset yielding a dividend of \$1 per year for 10 years would have a price path (ignoring discounting) of \$10, \$9,...

to its 1929 level until the end of World War II; however, from that point on average debt/equity remained close to .24 (standard deviation .036) for twenty-five years before rising again.

The issue of whether all or most tire manufacturers were publicly traded corporations is more difficult. Given the small firm sizes during the early years of the industry's development, and the almost "venture capital" nature of the business at that time, it is unlikely that many early participants in the tire market were publicly traded. However, given the tremendous growth enjoyed by firms that managed to remain in the industry, it is likely that all survivors eventually became publicly traded. Thus it is probable that the fraction of automobile tire firms that were publicly traded rose significantly over time. The method adopted for comparing the model and data, described below, tries to take this into account.

The data are taken from Cowles (1939) and cover the period 1906-1938. There are two series: an index of the stock prices of firms in the Automobile Tire and Rubber Industry and an index of the stock prices of all firms. Figure 4 displays the tire and rubber firm index relative to the all firms index;[15] units are chosen so that the relative value equals unity in 1906. The dominant feature of this series is its rapid increase and subsequent decline over the 1915-1925 period. The peak occurred in 1919, prior to the peak in firm numbers (1922). Note the variability in the early part of the series.

The figure also contains a time series calculated from the model, in particular, the output-weighted average value of firms in the industry relative to the value of participation elsewhere, again assuming a refinement date of 1913, its expected value. The point of weighting by output is that since it is presumably the larger firms in the tire industry that were publicly traded, focusing

[15] Division by the value of all stocks removes the the effects of both general economic growth and price level changes. Moreover, the model is forced to confront movements in the tire industry data that merely reflect trends in the price of all stocks, the general increase in stock prices during the 1920's, for example.

on the larger firms in the model economy makes it more likely that discrepancies between the model and data are due to failures of the model rather than differences in the way the theoretical and empirical indices are calculated.[16]

The calculations based on the model clearly show the main feature of the data, namely the increase and subsequent decline in share values; the bumpy time path of values prior to the explosion is also apparent. The predicted values display these features because, first, the arrival of the refinement is bad news for incumbents, so that the index drops at the refinement date, and thus before firms begin to exit. This is because the refinement foreshadows a rapidly declining product price, as shown in Figure 3(a), from which the shakeout follows. Second, as time passes and some firms establish themselves as early winners in the innovation race, the index rises sharply, reflecting those firms' enormous increase in both market share and value. Finally, the index declines as the innovation diffuses, dissipating the rents earned by early innovators .

2.6 Inventions

The model attributes the dynamics of firm numbers to technological advance. In light of the fact that the most familiar engineering advances in the tire industry occurred well after the period during which the industry was evolving, is this a plausible explanation?

The most well-known innovations are the development and wide-spread use of Rayon as the fabric from which cords are made (late 1930's), Rayon's subsequent replacement by Nylon (late 1940's) and then polyester (early 1960's), the replacement of natural with synthetic rubber (early 1940's), tubeless tires (1950's), the belted bias tire design (late 1960's), and finally, radial tires (late 1960's and early 1970's).[17]

[16]Other methods of focusing on larger firms– for example, including only the top decile– were also employed with minor impact on the conclusions that follow.
[17]*McGraw-Hill Encyclopedia of Scince and Technology*, 1992.

These advances are significant improvements, but it is also evident that at least three fundamental innovations occurred long before any of these. In *The House of Goodyear* (1939), Hugh Allen describes how, in the first decade of the century, "clincher" tires, which had to be stretched over the rim, were replaced by the more durable and easier-to-mount straight side tires, the basic design of which became the standard. Likewise, in 1913 the "cord" tire, in which corded fabric replaced the square-woven "duck" fabric as the material providing tires with strength and body, solved the problem of the excessive wear that had previously limited the life of a straight side tire to a few thousand miles. Finally, in 1916 the Banbury mixer eliminated the slow, space-intensive and hazardous process of mixing rubber with other compounds, and facilitated large scale production; in particular, it accelerated the mixing process by more than an order of magnitude (Allen, P. 45)[18]

The key property of whatever invention(s) preceded the shakeout is that it *increased the optimal scale of any firm that implemented it.* For example, because it saved on space, installing the Banbury mixed allowed a much greater volume of output to be produced on the innovator's *existing* premises and with fewer labor inputs, lowering marginal cost and raising the optimal scale. The major inventions that came later apparently did not raise the optimal scale of firms by enough to necessitate any further shakeout episodes.

3 Conclusion

This paper explains a nonmonotonic time path of firm numbers as the response of competitive firms to, first, the opportunity to innovate, and later, the relative failure to do so. In the U.S. Automobile Tire industry, several keys inventions appeared in the 1910-20 period. Once put to

[18] While describing the technological improvements of the 1908-1920 period, principally the corded tire and the Banbury mixer, Allen notes that the best available tire, the straight side, would not be a success unless some way to cut its production cost considerably; for example, a set of tires for a Packard cost $500.

work they allowed a dramatic increase in scale. Firms that were able to implement early were rewarded with growth in output and value; the others joined a mass exodus. This technology-based explanation for the shakeout in the tire industry is especially compelling because it is consistent with what stock price data reveal about profit opportunities– namely that the future of the tire industry was not a rosy one for most incumbents, but that early adoption of new technology offered great rewards. The main alternative explanation– that the shakeout was caused by the fares of the automotive industry– does not readily accommodate the timing of the shakeout in the tire industry.

Table 1

	Parameter	Estimate
Constant in Demand	d_0	91.56
1/(Elasticity of Demand)	d_1	1.311
Cost Parameter	c	206.98
Alternative Reward	π^a	.0759
Cost Improvement Factor − 1	θ	96.22
General Growth	g	1.0293
Refinement Hazard	ρ	.1251
Pre-refinement Low Tech Probability	β	.0165
Post-refinement Low Tech Probability	r^ϕ	.1141
Post-refinement High Tech Probability	r	.0192

Appendix– Data

t	f_t	Q_t	p_t	t	f_t	Q_t	p_t	t	f_t	Q_t	p_t	t	f_t	Q_t	p_t
1906	10	–	–	1923	246	45	2.350	1940	52	59	1.348	1957	42	107	1.251
1907	29	–	–	1924	213	52	1.984	1941	53	62	1.376	1958	43	97	1.232
1908	29	–	–	1925	184	61	2.061	1942	50	66 (15)	1.512	1959	44	118	1.149
1909	38	–	–	1926	165	62	2.070	1943	49	70 (20)	1.477	1960	44	120	1.093
1910	38	2	–	1927	146	64	1.581	1944	46	74 (33)	1.427	1961	43	117	1.075
1911	46	3	–	1928	132	78	1.355	1945	45	78 (45)	1.341	1962	40	134	1.001
1912	54	5	–	1929	121	69	1.166	1946	46	82	1.241	1963	39	139	1.024
1913	74	6	7.653	1930	96	51	1.126	1947	51	96	1.040	1964	37	158	.998
1914	94	8	6.309	1931	81	49	1.105	1948	51	81	.989	1965	36	168	.992
1915	106	12	5.595	1932	64	40	1.103	1949	49	76	.968	1966	34	177	1.00
1916	118	19	5.379	1933	62	45	1.180	1950	46	93	1.103	1967	32	163	1.00
1917	133	26	5.656	1934	76	47	1.229	1951	45	83	1.203	1968	32	203	.987
1918	143	23	5.574	1935	56	49	1.219	1952	45	90	1.142	1969	32	208	.932
1919	144	33	4.431	1936	54	56	1.245	1953	43	96	1.111	1970	30	190	.937
1920	181	32	4.250	1937	53	53	1.421	1954	40	89	1.135	1971	32	216	.9
1921	199	29	3.664	1938	51	41	1.497	1955	36	112	1.266	1972	31	236	.872
1922	275	41	2.522	1939	50	1.529		1956	42	100	1.310	1973	38	223	.837

Figures in parentheses are the unadjusted data for World War two. Sources:

1. Firms– Thomas Register of American Manufactures;
2. Output (Millions)– U.S. Department of Labor, BLS; and
3. Price Index (1967=1)– U.S. Department of Labor, BLS, divided by the Consumer Price Index.

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Figure 1
Number of Firms and Relative Share Values in the U.S. Automobile Tire Industry, and Automobile Sales

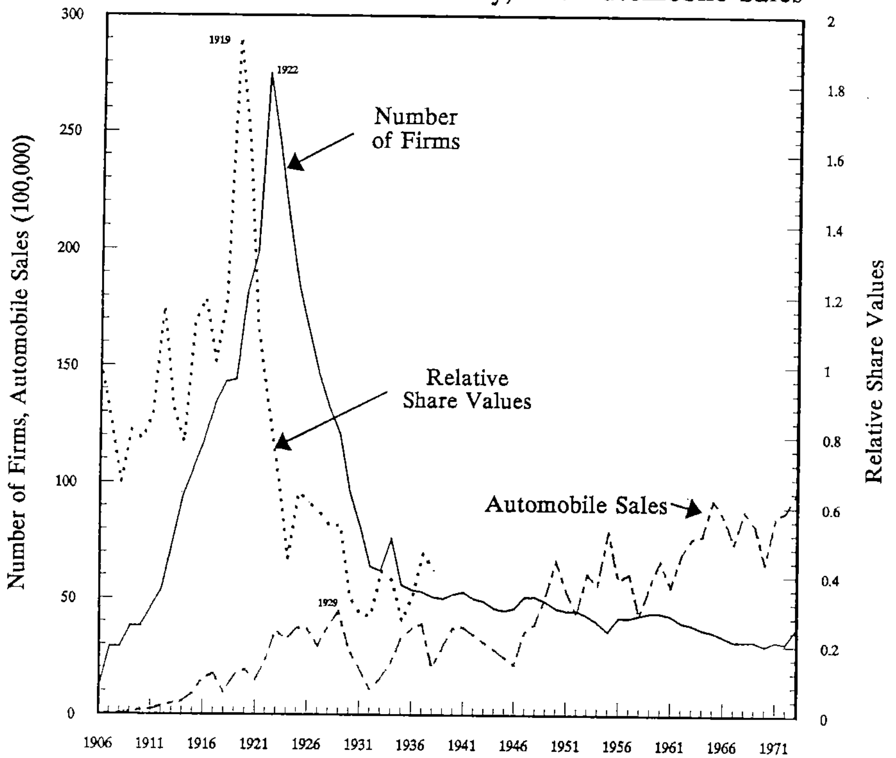

Figure 2
Price and Quantity in the U.S. Automobile Tire Industry

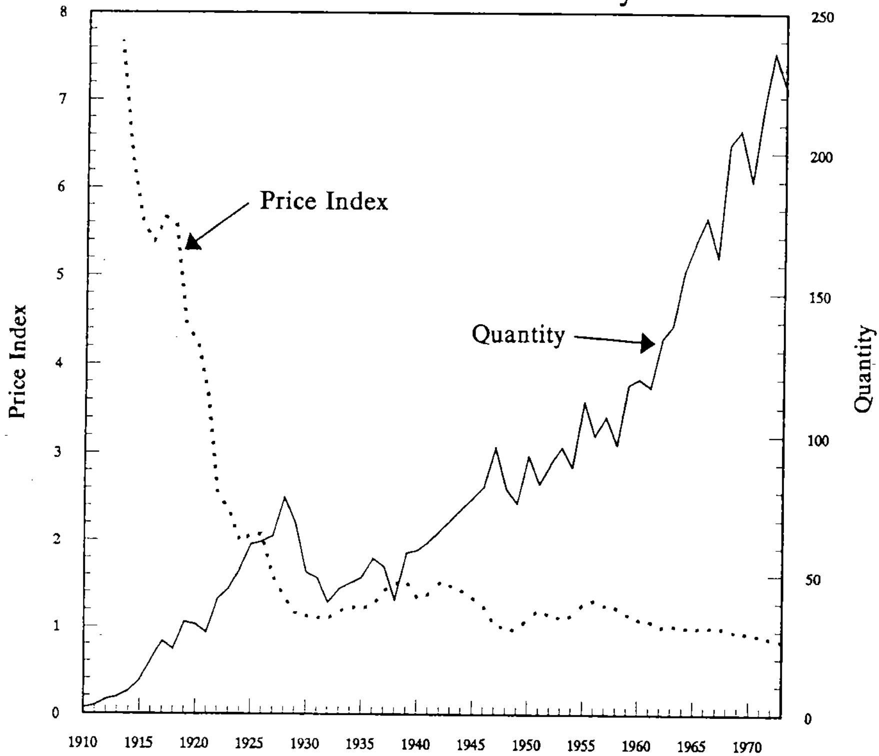

Figure 3
a) Actual and Predicted
Firm Numbers

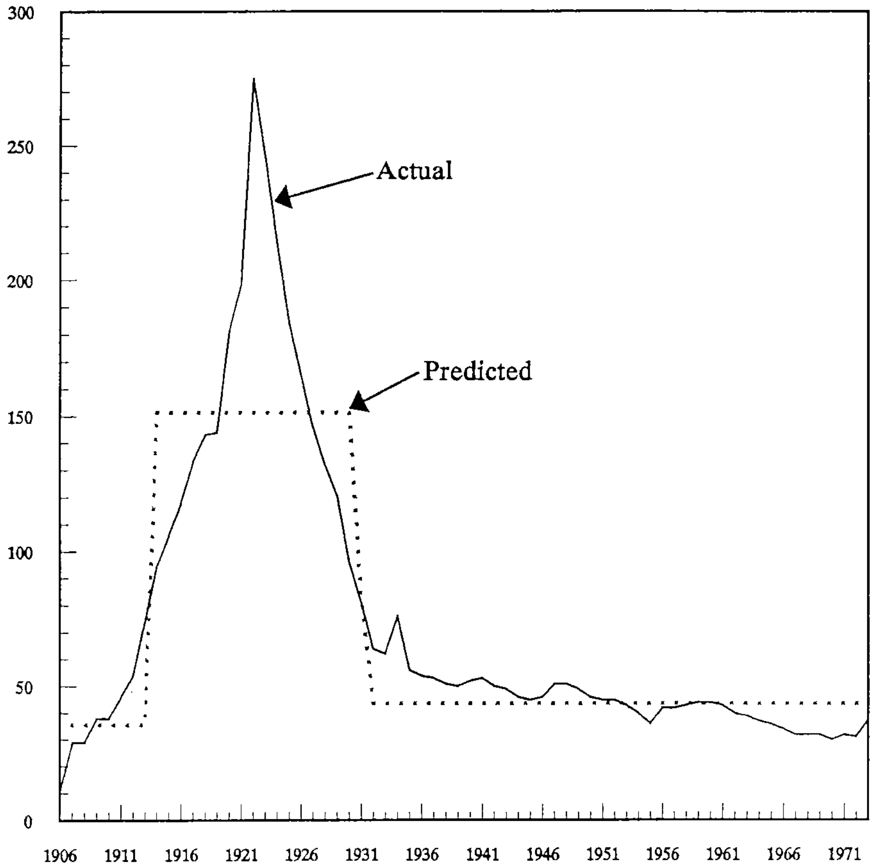

Figure 3
b) Actual and Predicted Quantity

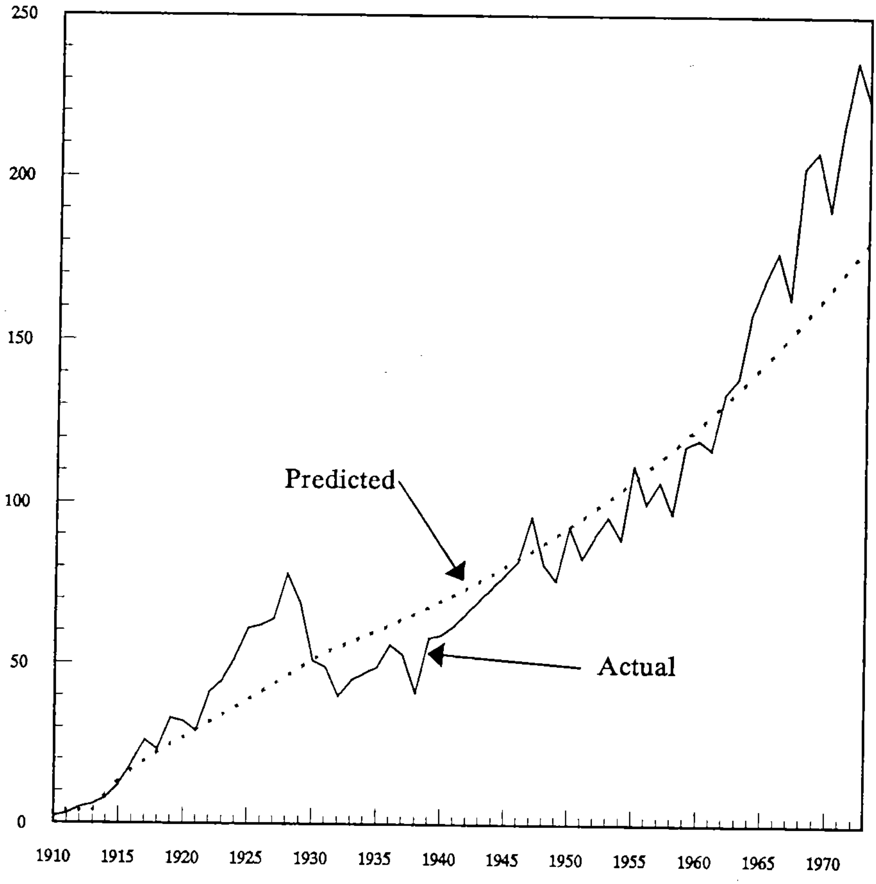

Figure 3
c) Actual and Predicted Price Index

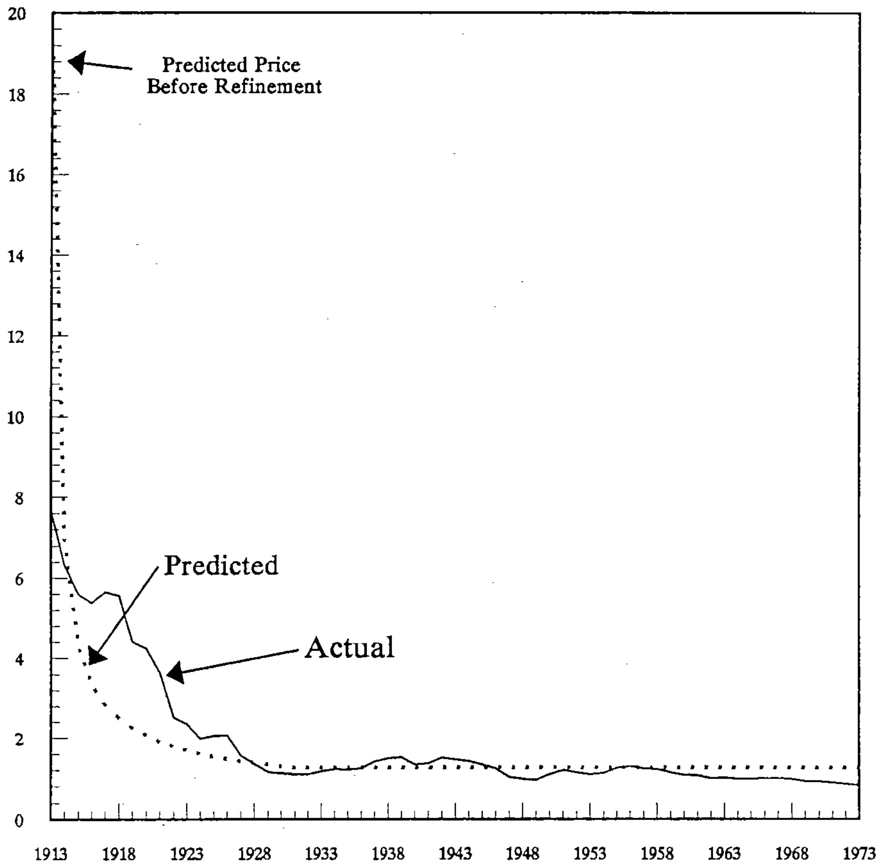

Figure 4
Actual and Predicted Stock Price Index