Entry, Exit, Growth, and Innovation over the Product Life Cycle

By STEVEN KLEPPER *

Regularities concerning how entry, exit, market structure, and innovation vary from the birth of technologically progressive industries through maturity are summarized. A model emphasizing differences in firm innovative capabilities and the importance of firm size in appropriating the returns from innovation is developed to explain the regularities. The model also explains regularities regarding the relationship within industries between firm size and firm innovative effort, innovative productivity, cost, and profitability. It predicts that over time firms devote more effort to process innovation but the number of firms and the rate and diversity of product innovation eventually wither. (*JEL* L10)

A similar view has emerged from a number of disciplinary perspectives about how technologically progressive industries evolve from birth through maturity.[1] When industries are new, there is a lot of entry, firms offer many different versions of the industry's product, the rate of product innovation is high, and market shares change rapidly. Despite continued market growth, subsequently entry slows, exit overtakes entry and there is a shakeout in the number of producers, the rate of product innovation and the diversity of competing versions of the product decline, increasing effort is devoted to improving the production process, and market shares stabilize. In some quarters, this evolutionary pattern has come to be known as the product life cycle (PLC).

While numerous authors have contributed to this description, perhaps the most influential have been William J. Abernathy and James M. Utterback.[2] Building on the work of Dennis C. Mueller and John E. Tilton (1969) and using the automobile industry as a leading case, they depict the PLC as driven by the way new technologies evolve. They stress that when a product is introduced, there is considerable uncertainty about user preferences (even among the users themselves) and the technological means of satisfying them. As a result, many firms producing different variants of the product enter the market and competition focuses on product innovation. As users experiment with the alternative versions of the product and producers learn about how to improve the product, opportunities to improve the product are depleted and a defacto product standard, dubbed a dominant design, emerges. Producers who are unable to produce efficiently the dominant design exit, contributing to a shakeout in the number of producers. The depletion of opportunities to improve the product coupled with locked-in of the dominant design leads to a decrease in product innovation. This in turn reduces producers' fears that investments in the production process will be rendered obsolete by technological change in the

* Department of Social and Decision Sciences, Carnegie Mellon University, Pittsburgh, PA 15213. I thank Wesley Cohen, Mark Kamlet, Jon Leland, John Miller, Richard Nelson, Ken Simons, Peter Swann, Bill Williams, and participants at the 1992 Conference of the International Joseph A. Schumpeter Society, the 1992 Conference on Market Processes and the Dynamics of Corporate Networks, Wissenschaftszentrum Berlin, and the Industrial Organization Seminars at the University of Maryland, Berkeley, Penn State, and the London School of Economics for helpful comments. The paper was greatly improved by the unstinting suggestions of two anonymous referees and the co-editor, Preston McAfee.

[1] See, for example, Oliver E. Williamson's (1975) account of how economists depict the evolution of new industries, Kim B. Clark's (1985) description of how technology and internal firm organization change over the course of industry evolution, and how a business consultant, Philip G. Drew (1987), describes the way business schools depict the evolution of industries.

[2] See in particular James M. Utterback and William J. Abernathy (1975) and Abernathy and Utterback (1978).

product. Consequently, they increase their attention to the production process and invest more in capital-intensive methods of production, which reinforces the shakeout of producers by increasing the minimum efficient size firm.

While this view has helped to popularize the PLC, it rests critically on the notion of a dominant design, an imprecise concept that does not appear to apply to all new products, especially ones for which buyer tastes are diverse (Michael E. Porter, 1983). Furthermore, it incorporates some questionable assumptions about technological change. It assumes that product and process innovation are inextricably linked and that firms will not attend to the production process until product innovation has slowed sufficiently. Yet the history of the automobile industry and others, such as tires and antibiotics, indicates that great improvements were made in the production process well before the emergence of any kind of dominant design (S. Klepper and Kenneth L. Simons, 1993). Indeed, many of these improvements were based on human and physical investments that were not rendered obsolete by subsequent major product innovations. The dominant-design view also minimizes the influence of industry demand on incentives to innovate, attributing the slowdown in product innovation and rise in process innovation entirely to the depletion of opportunities for product innovation and the emergence of a dominant design. While the relative importance of demand and supply factors has been hotly debated (David C. Mowery and Nathan Rosenberg, 1982), it has never been questioned that demand factors play an important role in shaping the rate and direction of technological change.

This paper proposes a new explanation for the PLC. Empirical regularities characterizing the PLC are first identified. A formal model is then constructed to explain the regularities. The model builds on recent theories of industry evolution (Richard R. Nelson and Sidney G. Winter, 1982; Boyan Jovanovic, 1982) and efforts to model the link between market structure and R&D (Nelson and Winter, 1978; Partha Dasgupta and Joseph Stiglitz, 1980; Therese M. Flaherty, 1980). The model focuses on the role of firm innovative capabilities and size in conditioning firm R&D spending, innovation, and market structure. Following various theoretical models of asymmetric industry structure (Flaherty; Avner Shaked and John Sutton, 1987), it incorporates the notion that the value of a unit cost reduction achieved through innovation is proportional to the level of output produced by the firm. Coupled with convex adjustment costs, this imparts an advantage to the earliest entrants which eventually causes a cessation in entry and a shakeout in the number of producers. It also provides firms with a greater incentive to engage in process innovation as they grow, which leads to an increase over time in their efforts to improve the production process. Firms are also assumed to have different capabilities that lead them to pursue different types of product innovations, a theme promoted by Nelson (1981) and used by Wesley M. Cohen and Klepper (1992) to explain differences within industries in firm R&D intensities. This provides the basis for explaining the decline in product innovation that occurs over time, linking it to the decline in the number of competitors brought about by the shakeout of producers. It is shown that the model can also explain various cross-sectional regularities that have accumulated concerning the relationship within industries between firm size and firm R&D effort, R&D productivity, cost, and profitability. Thus, the model provides a unified explanation for a wide range of temporal and cross-sectional regularities concerning industry evolution and firm behavior.

The paper is organized as follows. In Section I, the prominent features of the PLC are summarized. In Section II, the model is specified. In Section III, preliminary implications of the model are developed. In Section IV, the model is shown to explain all the prominent features of the PLC. In Section V, the model is used to explain various cross-sectional regularities between firm size, R&D, and firm performance. In Section VI, the implications of the model are discussed and extensions of the model are considered.

I. The Nature of the Product Life Cycle

The depiction of industry evolution conveyed in the PLC is based upon case studies and quantitative analyses of the evolution of new industries. In this section, six regularities concerning how entry, exit, market structure, and technological change vary from the birth of technologically progressive industries through maturity are summarized. While every industry has its idiosyncrasies, these regularities provide a composite picture of the evolution of technologically progressive industries.

The first two regularities pertain to entry and exit. Michael Gort and Klepper (1982) and Klepper and Elizabeth Graddy (1990) examine the annual time path in the number of producers for 46 major new products beginning with their commercial inception. Utterback and Fernando F. Suárez (1993) also consider the time path in the number of producers as well as the paths in the number of entrants and exits for 8 products subject to considerable technological change. Klepper and Simons (1993) review the entry and exit paths for 2 of the products studied by Utterback and Suárez and 2 other products subject to considerable technological change. Two patterns emerge from these studies concerning the nature of industry evolution in technologically progressive industries:

At the beginning of the industry, the number of entrants may rise over time or it may attain a peak at the start of the industry and then decline over time, but in both cases the number of entrants eventually becomes small.

The number of producers grows initially and then reaches a peak, after which it declines steadily despite continued growth in industry output.[3]

[3] These are general tendencies, and exceptions can always be found. Of greater significance is the possibility that these patterns reflect a bias in the way new products are typically defined. If these patterns tend to be interrupted by major innovations but the innovations are defined as creating new products subject to their own product life cycles, the patterns could be artifactual. The bulk of the new products that have been studied, however, did not experience such major innovations until many years after they were introduced, and their evolution was generally characterized by long initial periods during which the characteristic patterns in entry and the number of firms were observed.

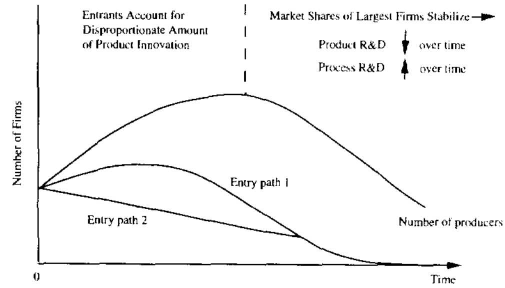

FIGURE 1. TEMPORAL PATTERNS OF ENTRY, NUMBER OF PRODUCERS, MARKET SHARES, AND INNOVATION

These patterns are illustrated in Figure 1. Two alternative paths for entry are depicted. In both cases, entry eventually becomes small and the number of firms rises initially and then declines over time. Related to these two patterns are regularities in the way firm market shares change over time. Although market-share data over an extended time period are not available for many products, Edwin Mansfield (1962) and Burton H. Klein (1977 pp. 89–128) have examined how the market shares of the leading producers of automobiles, tires, aircraft, petroleum, and steel changed over time. Their findings, which accord with a number of case studies, suggest a third regularity which is noted in Figure 1:

Eventually the rate of change of the market shares of the largest firms declines and the leadership of the industry stabilizes.

The other three regularities about the PLC pertain to technological change. Because technological change is more difficult to quantify, the regularities are based on a number of case studies[4] and two samples of innovations for a

[4] These include Abernathy (1978) and Abernathy et al. (1983) for automobiles, Klein (1977) for automobiles and aircraft, Tilton (1971) and Jerome Kraus (1973) for transistors, Kenneth Flamm (1988) and Philip Anderson and Michael J. Tushman (1990) for computers, Arthur A. Bright (1949) and James R. Bright (1958) for light bulbs, Thomas J. Prusa and James A. Schmitz (1991) for PC software, and Abernathy and Utterback (1978) and Utterback and Suárez (1993) for collections of products. For further detail, see Klepper (1992).

limited number of industries in the United States (Utterback and Abernathy, 1975) and the United Kingdom (C. De Bresson and J. Townsend, 1981). These studies suggest that for industries with rich opportunities for both product and process R&D, three patterns in product and process innovation can be identified:[5]

The diversity of competing versions of the product and the number of major product innovations tend to reach a peak during the growth in the number of producers and then fall over time.

Over time, producers devote increasing effort to process relative to product innovation.

During the period of growth in the number of producers, the most recent entrants account for a disproportionate share of product innovations.

These three regularities are also noted in Figure 1. Together, the six regularities laid out above and summarized in Figure 1 provide the focus for the theoretical analysis of the paper.

II. The Model

The model depicts the evolution from birth through maturity of an industry with rich opportunities for product and process innovation. Two aspects of innovation are featured. First, following Jacob Schmookler (1966) and a number of theoretical models (for example, Dasgupta and Stiglitz, 1980; Shaked and Sutton, 1987), the demand for a firm's product is assumed to condition its incentive to innovate. This is assumed to be manifested differently for process and product innovation. Process innovation is principally designed to lower a firm's average cost of production. Since the value of a reduction in average cost is proportional to the total output of the firm, it is assumed that the incentive for process innovation is conditioned by the total quantity demanded of the firm's product. Product innovations, in contrast, are often designed to attract new buyers for a product. Accordingly, it is assumed that the incentive for product innovation is conditioned by the demand of new buyers. Second, firms are assumed to be randomly endowed with distinctive capabilities which influence the kinds of innovations they develop. The idea of distinctive firm competencies lies at the heart of the business-strategy literature (Porter, 1980) and its relevance for innovation appears prominently in many industry case studies.[6] It is assumed that these differences in capabilities manifest themselves principally in product innovations, where firms often specialize in innovations that service distinctive types of users (Eric von Hippel, 1988). In contrast, process innovations tend to be incremental and based on information that firms commonly generate through production (compare Bright, 1958; Samuel Hollander, 1965).

The model is stylized to highlight the two featured aspects of innovation. It has the following structure. Time is discrete. In each period, incumbent firms decide whether to

[5] The three patterns are ascribed only to products with rich opportunities for both product and process innovation because the bulk of the products for which patterns in innovation have been studied are, not surprisingly, ones with such characteristics. Indeed, Abernathy (1978 p. 84), K. Pavitt and R. Rothwell (1976), and Porter (1983 pp. 23–24), among others, contend that products without rich opportunities for both product and process innovation do not follow the prototypical PLC. Examples cited as exceptions to the PLC include synthetic fibers and plastics, which are claimed to be relatively homogeneous and primarily subject to process but not product innovation, and heavy electrical equipment, which is produced in small batches and is claimed to be subject primarily to product and not process innovation. While no evidence is presented to buttress these claims and not all observers subscribe to them (for example, see David A. Hounshell [1988] regarding synthetic fibers), it is important to recognize that the evidence regarding innovation during the PLC is primarily based on products with rich opportunities for both product and process innovation. This is reflected in the model, which presupposes that the joint nature of product and process innovation drives the PLC.

[6] For example, a number of studies emphasize how significant innovations can be traced back to expertise acquired fortuitously. This is featured in Hugh G. J. Aitken's (1985) analysis of early radio innovations, Flamm's (1988) discussion of the influence of government sponsored cryptography efforts during World War II on subsequent innovation by computer firms, and Klein's (1977 pp. 89–109) discussion of the skills brought into the automobile industry at the turn of the century by entrepreneurs with experience in mass production and interchangeable parts manufacture.

remain in the industry and a limited number of potential entrants decide whether to enter. All firms produce a standard product. They decide how much process R&D to perform, which determines the average cost of the standard product. They also decide how much product R&D to perform. Firms randomly differ in their product innovation expertise, which influences their success at product R&D. In each period, successful product innovators develop a distinctive product innovation which they combine with the standard product to market a unique, distinctive product. Distinctive products appeal to all buyers, but only new buyers pay the premiums for them, with each distinctive product sold to a different class of new buyers. All firms monitor the product innovations of their rivals. This enables them to imitate all product innovations one period after they are introduced and incorporate them into the standard product at no additional production cost. When the last period's product innovations are incorporated into the standard product, buyers of the distinctive products become buyers of the standard product and the demand for the standard product by all other buyers increases, causing the demand curve for the standard product to shift to the right. Producers share in the expansion in demand for the standard product in proportion to their prior output and decide how much further to expand their output subject to a cost of adjustment. All decisions are made to maximize current profits, firms are price takers, and in each period the price of the standard product clears the market.

The model is formally specified as follows. In each period t, there are K_t potential entrants. As firms enter and others randomly develop the innovative capabilities required to enter, K_t changes. A priori no restrictions are placed on whether K_t rises or falls over time; this may differ across industries and also within industries over time. Each potential entrant is randomly endowed with innovative expertise which it cannot modify over time. Let s_i denote the innovation expertise of firm i, which it knows prior to entry, and $s_{\max}$ the maximum possible innovation expertise. To simplify the dynamics of the model, it is assumed that in each period there are one or more potential entrants with innovative expertise $s_{\max}$ and the cumulative distribution of innovative expertise is the same for the potential entrants in each period. This distribution is denoted as $H(s)$, where $H(s)$ is assumed to be continuous for all $s < s_{\max}$ and $H(s_{\max}) = 1$ by definition.

The firm's innovative expertise influences its success at product R&D. The probability of firm i developing a product innovation in period t is $s_i + g(\mathrm{rd}_{it})$, where rd_{it} is its spending on product R&D and the function $g(\mathrm{rd}_{it})$ reflects the opportunities for product innovation. Each successful innovator adds its innovation to the standard product and markets a distinctive variant of the industry's product, which it sells at a price exceeding the price of the standard product, reflecting the value of its innovation. Distinctive variants are assumed to appeal to all buyers but only new buyers have a positive demand for them at the prices charged, with each distinctive variant purchased by a different class of new buyers. After one period, all product innovations are copied and incorporated into the standard product, so successful innovators have a one-period monopoly over their distinctive variants. Let G denote the one-period gross monopoly profit (before subtracting the amount spent on product R&D) earned by each seller of a distinctive variant. It is assumed that $g'(\mathrm{rd}_{it}) > 0$ and $g''(\mathrm{rd}_{it}) < 0$ for all $\mathrm{rd}_{it} \geq 0$, reflecting diminishing returns, and that $g'(0)G > 1$, which ensures $\mathrm{rd}_{it} > 0$ for all i, t. In order to be able to imitate costlessly the innovations of its rivals, which is required to market a distinctive product variant and also the standard product, firms monitor the innovations of their rivals at a cost of F per period. Thus, if a firm engaged in only product innovation and did not produce the standard product, its expected profits in period t would be $[s_i + g(\mathrm{rd}_{it})]G - \mathrm{rd}_{it} - F$. To simplify the model, it is assumed that $F > [s_i + g(\mathrm{rd}_{it})]G - \mathrm{rd}_{it}$ for all rd_{it}. This ensures that in order to have nonnegative expected profits, all firms must produce the standard product.

Let $Q_t = f_t(p_t)$ denote the total market demand for the standard product in period t, where Q_t is the quantity demanded, p_t is the price of the standard product, and $f_t(p_t)$ is the market demand schedule for the standard product in period t. Over time, $f_t(p_t)$ shifts to the right at every price as last period's product innovations are incorporated into the standard product. It is assumed that $f_t(p_t)$ is continuous and downward sloping for all t. Let Q_{it} denote the output of the standard product by firm i in period t. It is determined as follows. Assuming that p_t falls over time (this will be shown in the next section), the total quantity demanded, Q_t, expands over time. All firms sell the same standard product at the same price. New buyers are assumed to choose a seller based on a stochastic learning process in which the probability of a firm attracting a new buyer is proportional to its sales of the standard product in the prior period, Q_{it-1}. It is assumed that it is optimal for a buyer to continue purchasing from the same firm as long as the firm remains in the market. Accordingly, it is assumed that incumbents in period t experience a rise in their sales of the standard product from Q_{it-1} in period $t-1$ to $Q_{it-1}(Q_t/Q_{t-1})$ in period t, where Q_t/Q_{t-1} denotes the growth in the total quantity demanded of the standard product from period $t-1$ to t. If desired, the firm can expand its output further, resulting in an increase in its market share of the standard product relative to period $t-1$. To do so, it must incur an adjustment cost of $m(\Delta q_{it})$, where Δq_{it} is the expansion in its output in period t above $Q_{it-1}(Q_t/Q_{t-1})$. The function $m(\Delta q_{it})$ is such that $m'(0) = 0$, $m'(\Delta q_{it}) > 0$ for all $\Delta q_{it} > 0$, and $m''(\Delta q_{it}) > 0$ for all $\Delta q_{it} \geq 0$, with $m'(\Delta q_{it})$ growing without bound as Δq_{it} increases, reflecting increasing marginal adjustment costs.[7]

The average cost of production of the standard product for firm i is assumed to be independent of Q_{it} and equal to $c - l(\mathrm{rc}_{it})$, where rc_{it} is the amount spent on process R&D by firm i in period t and the function $l(\mathrm{rc}_{it})$ reflects the opportunities for process innovation. Following Flaherty (1980), cost in period t is a function only of process R&D in period t. It is assumed that as rc_{it} increases, $l(\mathrm{rc}_{it})$ asymptotically approaches an upper bound and $l'(\mathrm{rc}_{it}) > 0$ and $l''(\mathrm{rc}_{it}) < 0$ for all $\mathrm{rc}_{it} \geq 0$, reflecting diminishing returns. Further, it is assumed that $l'(0)Q_{\min} > 1$, where $Q_{\min}$ is the smallest level of output ever produced by any firm. This ensures $\mathrm{rc}_{it} > 0$ for all i, t.

Given the assumptions, the expected profit of firm i in period t, $E(\Pi_{it})$, can be expressed as

$$(1) \quad E(\Pi_{it}) = [s_i + g(\mathrm{rd}_{it})]G - \mathrm{rd}_{it} + [Q_{it-1}(Q_t/Q_{t-1}) + \Delta q_{it}] \times [p_t - c + l(\mathrm{rc}_{it})] - \mathrm{rc}_{it} - m(\Delta q_{it}) - F,$$

where $[s_i + g(\mathrm{rd}_{it})]G - \mathrm{rd}_{it}$ is the firm's expected net profit from product R&D after subtracting the cost of its product R&D, $[Q_{it-1}(Q_t/Q_{t-1}) + \Delta q_{it}][p_t - c + l(\mathrm{rc}_{it})] - \mathrm{rc}_{it} - m(\Delta q_{it})$ is its net profit from producing the standard product after subtracting both its spending on process R&D and the costs of adjusting its output, and F is the cost of monitoring the innovations of its rivals. Expression (1) applies to entrants in period t as well as incumbents, with $Q_{it-1} = 0$ for entrants. All firms are assumed to be atomistic and price takers. In each period t they can project the market-clearing price for the standard product, p_t, but are uncertain about future prices and thus their prospects for survival. Accordingly, it is assumed they decide whether to be in the industry and if so, rd_{it}, rc_{it}, and Δq_{it}, to maximize current expected profits, $E(\Pi_{it})$. Let rd_{it}^*, rc_{it}^*, and Δq_{it}^* denote the profit-maximizing choices of rd_{it}, rc_{it}, and Δq_{it} and $E(\Pi_{it}^*)$ the expected profits of the firm at these choices. Potential entrants enter if $E(\Pi_{it}^*) > 0$, are indifferent about entering if $E(\Pi_{it}^*) = 0$, and do not enter if $E(\Pi_{it}^*) < 0$, where Δq_{it} defines their initial output of the standard product if they enter. Similarly, incumbents stay in the industry if $E(\Pi_{it}^*) > 0$, are indifferent about staying in if $E(\Pi_{it}^*) = 0$, and exit if $E(\Pi_{it}^*) < 0$. Once incumbents exit, their output of the standard product is lost.

The industry is assumed to start in period 1 when demand and technology for the product are such that there exists a price p_1 for which the quantity supplied by firms with

[7] If a firm wants to expand its market share, it will normally have to incur marketing costs to attract customers from its rivals. The assumption that $m''(\Delta q_{it}) > 0$ reflects the idea that the more the firm wants to increase its market share in any given period, the greater the marketing costs required for expansion at the margin.

nonnegative expected profits equals the quantity demanded, Q_1, where $Q_1 > 0$. Similarly, in every subsequent period p_t is assumed to clear the market. This requires that the quantity demanded in period t, $Q_t = f_t(p_t)$, equals the quantity supplied by producers in period t taking p_t as given:

$$(2)\quad Q_t = \sum_{i,t} \{ Q_{it-1}(Q_t / Q_{t-1}) + \Delta q_{it} \},$$

where the index i, t of the summation denotes that the summation is over firms i in the market in period t. In terms of the actual mechanism governing the change in price from period $t-1$ to t, the dynamics of the model are simplified by assuming that for all incumbent firms in period t, $dE(\Pi_{it}^*)/dp_t > 0$ for all prices p_t within a broad neighborhood of p_{t-1},[8] with the equilibrium price constrained to lie in this broad neighborhood. The existence of such a price in each period satisfying equation (2) is demonstrated in the next section. As will be shown, market clearing is achieved through the effects of p_t on Q_t, Δq_{it}, and on entry and exit in period t.[9]

The model is stylized to keep it tractable and to highlight the two key features of innovation that underlie it. Product innovations are assumed to be introduced into distinctive versions of the product and then incorporated into the products of all firms, which conforms to the way many products evolve over time.[10] This preserves the notion of an industry in which all firms produce the same product while allowing for (limited) product differentiation. Each product innovation is assumed to be sold to a different class of new buyers to reflect the idea that firms have different kinds of innovative expertise that lead them to service different groups of buyers. Coupled with the assumption that product innovations do not affect the demand for the standard product, this ensures that the incentive to engage in product innovation is determined solely by the demand of new buyers.[11] Differences in firm innovative abilities are structured so that they do not affect the firm's output of the standard product nor the amount spent on product or process R&D. Consequently, the firm's output of the standard product is related to the firm's R&D spending only through its effects on the returns from process R&D, which highlights the influence of the demand for the standard product on process R&D. Opportunities for innovation, as reflected in the functions $g(\mathrm{rd}_{it})$ and $l(\mathrm{rc}_{it})$, are assumed constant to abstract from the effects of changing technological opportunities on the firm's R&D spending. All decisions are based on current expected profits and process innovations are not cumulative to simplify the dynamics of the model and to reflect the limited horizons of firms in new industries. Many of these assumptions are reconsidered in the conclusion, where it is argued that the spirit and principal implications of the model would not change if the assumptions were relaxed.

[8] This condition requires that in each period t, the lower p_t then the lower the maximum possible expected profits of each firm, assuming the firm can sell as much of the standard product as it wants at p_t. The price of the standard product affects $E(\Pi_{it}^*)$ in two ways: through its effect on the profit per unit of the standard product, $p_t - c + l(\mathrm{rc}_{it})$, and through its effect on each firm's output of the standard product via the total quantity demanded of the standard product, Q_t. These two effects work in opposite directions—the lower p_t then the lower the firm's profit per unit on the standard product, ceteris paribus, but the greater the firm's total output of the standard product, ceteris paribus. Given that $l(\mathrm{rc}_{it})$ is bounded, at sufficiently low prices $E(\Pi_{it}^*)$ must be less than zero for all firms, hence at sufficiently low prices the first effect must dominate the second and $dE(\Pi_{it}^*)/dp_t > 0$. If $df_t(p_t)/dp_t = 0$ at the relevant prices (that is, the price elasticity of demand equaled zero), then p_t would have no effect on the firm's output of the standard product and it is easy to see from equation (1) that $dE(\Pi_{it}^*)/dp_t > 0$ for all prices. More generally, if suitable constraints are placed on the function $df_t(p_t)/dp_t$ at the relevant prices then $dE(\Pi_{it}^*)/dp_t > 0$ for all prices within a broad neighborhood of p_{t-1}.

[9] Note that if exit occurs in period t then $\Sigma_{i,t}\, Q_{it-1} < \Sigma_{i,t-1}\, Q_{it-1} = Q_{t-1}$, where the index i, $t-1$ denotes summation over firms in the market in period $t-1$. As developed in the next section, exit will be necessary for the market to clear in each period.

[10] For example, in automobiles innovations such as the electric starter and the inexpensive closed body were introduced into distinctive models and then copied widely by all manufacturers.

[11] This abstracts from strategic incentives to innovate associated with the preemption of rivals (Richard J. Gilbert and David M. G. Newbery, 1982) and cannibalism of prior innovations (Jennifer Reinganum, 1983, 1985).

III. Preliminary Results

In order to facilitate the proof of later results, a series of intermediate implications of the model are developed as lemmas. In deriving these lemmas, it is assumed that there exists a price p_t in each period that clears the market given the choices firms make about entry, exit, rd_{it}, rc_{it}, and Δq_{it} taking p_t as given. The existence of such a path for price is established at the end of this section.

The first results pertain to firms in the market in period t, including firms that entered the market during period t as well as earlier entrants. Differentiating (1) with respect to rd_{it}, rc_{it}, and Δq_{it} establishes the following first-order conditions for an interior maximum for each firm i in the market in period t:

$$(3) \qquad g'(\text{rd}_{it}^*)G = 1$$

$$(4) \quad [Q_{it-1}(Q_t/Q_{t-1}) + \Delta q_{it}^*]\, l'(\text{rc}_{it}^*) = 1$$

$$(5) \qquad m'(\Delta q_{it}^*) = p_t - c + l(\text{rc}_{it}^*),$$

where optimal values are denoted by an asterisk. Furthermore, for a firm to be in the market in period t, its expected profits in period t must be nonnegative. Given the assumption of $F > [s_i + g(\text{rd}_{it})]G - \text{rd}_{it}$ for all rd_{it}, a necessary condition for $E(\Pi_{it}) \geq 0$ is that for each firm i in the market in period t:

$$(6) \qquad p_t - c + l(\text{rc}_{it}^*) > 0.$$

Assuming $-l''(\text{rc}_{it}^*)[Q_{it-1}(Q_t/Q_{t-1}) + \Delta q_{it}^*] \times m''(\Delta q_{it}^*) > l'(\text{rc}_{it}^*)^2$ to ensure that the joint solution of (4) and (5) for rc_{it} and Δq_{it} is a maximum, the solutions to equations (3)–(6) will satisfy the second-order conditions. Consequently, for each firm i and period t, $\text{rd}_{it}^* > 0$, $\text{rc}_{it}^* > 0$, and $\Delta q_{it}^* > 0$, with these choices satisfying equations (3)–(6). Thus, all firms in the market in period t perform product and process R&D and increase their market share of the standard product relative to period $t-1$.

Conditions (3)–(6) imply two results which reflect the simplified nature of the model.

LEMMA 1: *For all i and t*, $\text{rd}_{it}^* = \text{rd}^*$, *where* rd^* *satisfies* $g'(\text{rd}^*)G = 1$.

PROOF:

The profit-maximizing value of rd_{it} is defined by equation (3), which is the same for all firms and does not change over time. Consequently, all firms spend the same amount rd^* on product R&D, where rd^* satisfies (3).

Analogous to $E(\Pi_{it}^*)$, let $V_{it}^* = [Q_{it-1}(Q_t/Q_{t-1}) + \Delta q_{it}^*][p_t - c + l(\text{rc}_{it}^*)] - \text{rc}_{it}^* - m(\Delta q_{it}^*)$ denote the firm's (incremental) profit from the standard product. Lemma 1 implies that the firm's incremental profit earned from product R&D in each period, $[s_i + g(\text{rd}_{it})]G - \text{rd}_{it}$, remains constant over time. Consequently, changes in the firm's expected profits over time arise only from changes in V_{it}^*. Accordingly, most of the analysis of the model focuses on the standard product.

The second result indicates that in each period t, firms in each entry cohort make the same choices for rc_{it} and Δq_{it} and have the same output and incremental profits from the standard product. Letting the values of these variables for entry cohort k in period t be denoted as rc_t^k, Δq_t^k, Q_t^k, and V_t^k, the following result is established.

LEMMA 2: *For all firms i that entered in period k and are still in the market in period* $t \geq k$, $\text{rc}_{it}^* = \text{rc}_t^k$, $\Delta q_{it}^* = \Delta q_t^k$, $Q_{it} = Q_t^k$, and $V_{it}^* = V_t^k$.

PROOF:

Since $Q_{it-1} = 0$ for entrants in period t, equations (4) and (5) imply rc_{it}^* and Δq_{it}^*, hence Q_{it} and V_{it}^*, must be the same for all entrants in t. It then follows from (4) and (5) that rc_{it}^*, Δq_{it}^*, Q_{it}, and V_{it}^* must be the same for these firms in every period they are in the market.

Lemmas 1 and 2 imply that in each period t the expected profits of firms that entered in the same period differ only according to their product-innovation expertise s_i. Consequently, in each period the distribution of $E(\Pi_{it})$ across firms in the same entry cohort will be the same as the distribution of s_i for these firms.

The firm's output in the prior period, Q_{it-1}, will determine its choice of rc_{it} and Δq_{it} and hence V_{it}. This is reflected in Lemma 3.

LEMMA 3: *For each firm i in the market in period t, the larger Q_{it-1} then the larger* rc_{it}, Δq_{it}, *and* V_{it}.

PROOF:

Differentiating (3)–(5) with respect to Q_{it-1} and rearranging yields

$$d\mathrm{rc}_{it}^* / dQ_{it-1} = g''(\mathrm{rd}_{it}^*)Gm''(\Delta q_{it}^*)l'(\mathrm{rc}_{it}^*) \times (Q_t / Q_{t-1}) / D$$

$$d\Delta q_{it}^* / dQ_{it-1} = g''(\mathrm{rd}_{it}^*)Gl'(\mathrm{rc}_{it}^*)^2 \times (Q_t / Q_{t-1}) / D$$

$$dV_{it}^* / dQ_{it-1} = \partial V_{it}^* / \partial Q_{it-1} = [p_t - c + l(\mathrm{rc}_{it}^*)](Q_t / Q_{t-1}),$$

where D is the determinant of the matrix of second partials of $E(\Pi_{it})$ with respect to rd_{it}, rc_{it}, and Δq_{it} evaluated at rd_{it}^*, rc_{it}^*, and Δq_{it}^*. Since $D < 0$ based on the second-order conditions and $p_t - c + l(\mathrm{rc}_{it}^*) > 0$ based on (6), each of these derivatives is positive. Therefore, the larger Q_{it-1} then the greater rc_{it}, Δq_{it}, and V_{it}.

Since Δq_{it}^* is determined by Q_{it-1} and $\Delta q_{it}^* > 0$ for all i, t, Lemmas 2 and 3 imply that in each period t the age of the firm fully determines rc_{it}, Δq_{it}, V_{it}, and Q_{it}, with each greater the older the firm. Coupled with Lemma 1, this implies that in each period t differences across firms in $E(\Pi_{it})$ are fully determined by two factors: the age of the firm and its product innovation expertise s_i.

Lemma 1 establishes the time path of rd_{it} for each firm while Lemmas 2 and 3 establish how rc_{it}, Δq_{it}, Q_{it}, and V_{it} vary across firms in each period. It is also possible to investigate how rc_{it}, Δq_{it}, Q_{it}, and V_{it} change over time for each firm. For incumbents, Q_{it} and rc_{it} change over time as follows.

LEMMA 4: *For each firm i in the market in periods t − 1 and t,* $Q_{it} > Q_{it-1}$ *and* $\mathrm{rc}_{it} > \mathrm{rc}_{it-1}$.

PROOF:

Since $\Delta q_{it} > 0$ for all i, t, it follows that $Q_{it} > Q_{it-1}$ for all i, t. Rewriting equation (4) as $Q_{it}l'(\mathrm{rc}_{it}^*) = 1$, it follows from $Q_{it} > Q_{it-1}$ and $l''(\mathrm{rc}_{it}) < 0$ for all rc_{it} that $\mathrm{rc}_{it} > \mathrm{rc}_{it-1}$.

The time paths for Δq_{it} and V_{it} for incumbents cannot be so easily characterized. Equation (5) indicates that for each incumbent Δq_{it} will change over time according to the time path of $p_t - c + l(\mathrm{rc}_{it})$, the firm's profit per unit of the standard product. The change in V_{it} over time will also depend on the time path in $p_t - c + l(\mathrm{rc}_{it})$. Lemma 4 implies that $l(\mathrm{rc}_{it})$ rises over time, but Lemma 5 below indicates p_t falls over time. Consequently, without further assumptions it cannot be determined whether Δq_{it} and V_{it} generally rise or fall over time for incumbents.

That p_t must fall over time can be easily established.

LEMMA 5: *For each period t,* $p_t < p_{t-1}$.

PROOF:

Recall that it was assumed that for each incumbent firm i in period t, $dE(\Pi_{it}^*)/dp_t > 0$ for all prices p_t within a broad neighborhood of p_{t-1}, with the equilibrium price in period t lying in this neighborhood. Lemma 5 is established by showing that for all prices $p_t \geq p_{t-1}$ in this neighborhood, the market cannot clear in period t. Suppose $p_t = p_{t-1}$. Then, Q_{it} must exceed Q_{it-1} for all producers in period $t-1$. This implies $E(\Pi_{it}^*) > E(\Pi_{it-1}^*) \geq 0$ for all producers in period $t-1$ and hence that no incumbent would exit in period t. The same condition must be true for all prices $p_t > p_{t-1}$ within a broad neighborhood of p_{t-1} given that $dE(\Pi_{it}^*)/dp_t > 0$ for all such prices. But every firm that remains in the industry will expand its market share, hence the market cannot clear if all firms remain in the industry. Therefore, p_t must be less than p_{t-1}.

In order for every firm that remains in the market to expand its market share, some firms must exit in every period. This will occur only if price falls over time. It must fall sufficiently in each period t that $E(\Pi_{it}^*)$ falls below zero for some firms in the market in period $t-1$, causing these firms to exit.

Using $p_t < p_{t-1}$, it is possible to characterize how the size of entrants, Δq_t^t, the process R&D of entrants, rc_t^t, and the profits of entrants from the standard product, V_t^t, change over time. Let s_t^k denote the minimum product innovation expertise in period t among firms that entered in period $k \le t$. It is also possible to characterize how s_t^t, the minimum product innovation expertise among entrants, changes over time. Over time, rc_t^t, Δq_t^t, V_t^t, and s_t^t change as follows.

LEMMA 6: *For all periods $l > k$, $\mathrm{rc}_l^l < \mathrm{rc}_k^k$, $\Delta q_l^l < \Delta q_k^k$, $V_l^l < V_k^k$, and $s_l^l > s_k^k$.*

PROOF:

The choices of rc_{it} and Δq_{it} for entrants in period t must satisfy equations (3)–(6) with $Q_{it-1} = 0$. These equations differ across periods only because p_t falls over time. To see how changes in p_t affect rc_t^t, Δq_t^t, and also V_t^t, set $Q_{it-1} = 0$ in (3)–(5) and differentiate with respect to p_t. This yields

$$d\mathrm{rc}_{it}^* / dp_t = g''(\mathrm{rd}_{it}^*)Gl'(\mathrm{rc}_{it}^*) / D > 0$$

$$d\Delta q_{it}^* / dp_t = g''(\mathrm{rd}_{it}^*)Gl''(\mathrm{rc}_{it}^*)\Delta q_{it}^* / D > 0$$

$$dV_{it}^* / dp_t = \partial V_{it}^* / \partial p_t = \Delta q_{it}^* > 0.$$

Given that $p_t < p_{t-1}$, it follows that rc_t^t, Δq_t^t, and V_t^t must fall over time. Furthermore, if V_t^t falls over time, the marginal entrant must earn greater incremental profits from product innovation over time, which implies s_t^t must rise over time.

Lemma 6 indicates that the minimum innovative expertise required for entry rises over time. Lemma 7 indicates that it eventually rises to the point where no further entry occurs.

LEMMA 7: *After some period, $s_t^t > s_{max}$ and no firms enter the industry.*

PROOF:

Recall that it was assumed that the distribution of innovative expertise $H(s)$ was such that at least one potential entrant in every entry cohort had innovative expertise $s_{\max}$. If $s_t^t \le s_{\max}$ for all t then in every period $E(\Pi_{it}^*) \ge 0$ for potential entrants with innovation expertise $s_{\max}$, hence $E(\Pi_{it}^*) > 0$ for all prior entrants with innovative expertise $s_{\max}$. Consequently, no incumbent with innovative expertise $s_{\max}$ would ever exit the industry. Since $\Delta q_{it} > 0$ for all firms that remain in the industry, firms with innovative expertise $s_{\max}$ will expand their market share in every period. This cannot, however, occur indefinitely, as eventually these firms would capture the entire market and would not be able to expand further without some of them exiting. This requires p_t eventually to fall to a level such that $E(\Pi_{it}^*) < 0$ for some incumbents with innovative expertise $s_{\max}$. At this point $E(\Pi_{it}^*) < 0$ for all potential entrants with $s_i = s_{\max}$. Since p_t falls over time, after this point $E(\Pi_{it}^*)$ will continue to be negative for potential entrants with $s_i = s_{\max}$, hence s_t^t will exceed $s_{\max}$ and no further entry will occur.

One final result that will be useful concerns how s_t^k differs across entry cohorts in each period. This is summarized as follows.

LEMMA 8: *In each period t, $s_t^l > s_t^k$ for $l > k$.*

PROOF:

In each period, $E(\Pi_{it}) \ge 0$ for producers. Given that V_{it}^* is lower the younger the firm based on Lemma 3, it follows that the minimum s_i required for survival must be greater for younger firms. Coupled with the fact that entrants start with higher minimum product innovation expertise than all prior entry cohorts based on Lemma 6, it follows that the younger the cohort of firms then the greater the minimum product innovation expertise of the cohort.

The various lemmas indicate how: (1) the price of the standard product changes over time; (2) the initial values of rd_{it}, rc_{it}, Δq_{it}, and V_{it} change over time for entrants; and (3) the values of rd_{it}, rc_{it}, and Q_{it} change over time for incumbents. Summarizing results, over time p_t declines, rd_{it} remains the same for entrants and incumbents, rc_{it}, Δq_{it}, and V_{it} decline over time for entrants, s_t^t rises over time for entrants, and rc_{it} and Q_{it} rise over time for incumbents after entry. The other time paths, which involve how Δq_{it}, V_{it}, and $E(\Pi_{it})$ change over time for incumbents after entry, cannot be characterized generally. The only pattern that must hold is that in each period, V_{it} and $E(\Pi_{it})$ must fall for some firms.

It was assumed that a price p_t existed in each period such that the market cleared given the choices of firms taking p_t as given. This will now be established via induction. It was assumed that such a price existed in period 1—this was how period 1 was defined. Suppose such a price exists in period $t-1$. It will be shown that a market-clearing price p_t then must exist in period t given the choices of firms taking this price p_t as given. Given that the market cleared in period $t-1$, $Q_{t-1} = \Sigma_{i,t-1} Q_{it-1}$, where the summation is over firms in the market in period $t-1$. In period t, p_t must satisfy equation (2), which can be expressed as

$$(7)\qquad f_t(p_t)\left\{1 - \sum_{i,t} Q_{it-1}/Q_{t-1}\right\} - \sum_{i,t} \Delta q_{it} = 0,$$

where the summation is over firms in the market in period t. In the proof of Lemma 5 it was established that p_t must be less than p_{t-1} and must induce some firms to exit; otherwise $1 - \Sigma_{i,t} Q_{it-1}/Q_{t-1} = 0$ since the market cleared in period $t-1$ and equation (7) would be violated given that $\Delta q_{it} > 0$ for each firm in the market. Given the assumption of $dE(\Pi_{it}^*)/dp_t > 0$, the lower p_t then the more firms for which $E(\Pi_{it}^*) < 0$ and thus the greater the number of firms exiting in period t. The more firms that exit then the greater $\{1 - \Sigma_{i,t} Q_{it-1}/Q_{t-1}\}$ and the smaller $\Sigma_{i,t} \Delta q_{it}$ in equation (7). Furthermore, the smaller p_t then the greater $f_t(p_t)$ and the smaller Δq_{it} for each firm, which reinforces the effect of exit on the market-clearing condition. Thus, as p_t decreases relative to p_{t-1}, $f_t(p_t)\{1 - \Sigma_{i,t} Q_{it-1}/Q_{t-1}\}$ rises and $\Sigma_{i,t} \Delta q_{it}$ falls in equation (7). Given that $l(\mathrm{rc}_{it})$ is bounded, at a low enough price $E(\Pi_{it}^*) < 0$ for each firm and all firms would exit the industry. Thus, at a low enough price $f_t(p_t)\{1 - \Sigma_{i,t} Q_{it-1}/Q_{t-1}\} - \Sigma_{i,t} \Delta q_{it} > 0$, whereas for prices $p_t \geq p_{t-1}$, $f_t(p_t)\{1 - \Sigma_{i,t} Q_{it-1}/Q_{t-1}\} - \Sigma_{i,t} \Delta q_{it} < 0$. Given that $f_t(p_t)$ and Δq_{it} are continuous functions of p_t and all firms are assumed to be atomistic and indifferent about being in the industry when $E(\Pi_{it}^*) = 0$, it then follows that there must be a price p_t which satisfies equation (7) and thus clears the market in period t.[12]

Note that the existence of such a path for price does not depend on positive entry in each period, nor does it depend on the time paths in the number of entrants, number of exits, and number of firms. These time paths are addressed in the next section.

IV. The Regularities of the PLC

Six propositions are developed in this section corresponding to each of the empirical regularities summarized in Section 2.

Consider the first regularity about entry over time. Let E_t denote the number of entrants in period t. The possible time paths in E_t implied by the model are characterized in Proposition 1.

PROPOSITION 1: *Initially the number of entrants may rise or decline, but eventually it will decline to zero.*

PROOF:

The entry process is such that $E_t = K_t(1 - H(s_t^i))$. Lemma 6 indicates s_t^i rises over time. Hence E_t will fall over time unless K_t rises over time at a sufficient rate, which cannot be ruled out a priori. Therefore, initially E_t may rise or

[12] The assumption that all firms are atomistic ensures the continuity of $f_t(p_t)\{1 - \Sigma_{i,t} Q_{it-1}/Q_{t-1}\} - \Sigma_{i,t} \Delta q_{it}$ as a function of p_t and hence the existence of a price p_t satisfying equation (7). A similar assumption is invoked in Jovanovic and Glenn H. MacDonald (1994) and Hugo A. Hopenhayn (1993) in their models of industry shakeouts (these are discussed further below). Alternatively, if firms were nonatomistic then the quantity supplied, $\Sigma_{i,t} Q_{it-1}(Q_t/Q_{t-1}) + \Sigma_{i,t} \Delta q_{it}$, could exceed the quantity demanded, $f_t(p_t)$, at all prices p_t insufficient to induce the marginal firm to exit but could fall short of the quantity demanded at all prices sufficient to induce the marginal firm to exit. Then, there would be no price that would clear the market in period t. Although beyond the scope of the paper, nonatomistic firms might be accommodated by allowing firms to maintain backlogs of unfilled orders so that unsatisfied demand at the equilibrium price in period t was satisfied through firm expansion in subsequent periods.

fall over time. Lemma 7 indicates that in either case, E_t will eventually decline to 0.

Proposition 1 can account for the two entry patterns reflected in Figure 1. Intuitively, in every period, incumbents have a lower average cost than entrants because they spend more on process R&D due to the greater output over which they can apply the benefits of their R&D. Entrants can nonetheless gain a foothold in the industry if they can earn sufficient profits from developing a distinctive product variant, which requires sufficient product-innovation expertise s_i. Over time, though, price is driven down and the advantage of incumbents over entrants grows, increasing the product-innovation expertise required for entry to be profitable. This reduces the percentage of potential entrants that enter over time, although the number of entrants can rise at any time if the number of potential entrants K_t rises sufficiently. Eventually, price is driven to a level such that regardless of their product-innovation expertise, the expected profits of all potential entrants are less than or equal to 0 and entry ceases.

The second regularity indicates that initially the total number of firms rises but eventually peaks and then declines steadily, as reflected in Figure 1. Proposition 2 indicates how this can be explained by the model.

PROPOSITION 2: *Initially the number of firms may rise over time, but eventually it will decline steadily.*

PROOF:

It was shown that p_t must fall over time in Lemma 5, and by a sufficient amount to cause some firms to exit in every period. Coupled with Lemma 7, which indicates entry must eventually stop, this implies that after some period the number of firms steadily declines. To see how the number of firms could rise over time at some point prior to this, consider without loss of generality the change in the number of firms between periods 1 and 2. This change equals the number of entrants in period 2, $K_2(1 - H(s_2^2))$, minus the number of exits in period 2, $K_1(H(s_2^1) - H(s_1^1))$. The only constraint on the number of entrants and exits comes from the requirement that the market must clear in period 2. All incumbents that remain in the industry in period 2 expand their market share. Therefore, in order for the market to clear in period 2, the total output of entrants in period 2, $K_2(1 - H(s_2^2))\Delta q_2^2$, must be less than the output exiters in period 2 would have produced if they had remained in the industry and maintained their market share, $K_1(H(s_2^1) - H(s_1^1))(Q_2/Q_1)\Delta q_1^1$. Since $\Delta q_2^2 < \Delta q_1^1$ based on Lemma 6, this condition can be satisfied even if $K_2(1 - H(s_2^2)) > K_1(H(s_2^1) - H(s_1^1))$. Thus, initially the number of firms may rise. Note that the number of firms could rise from period 1 to 2 even if $K_2 < K_1$, which would ensure that the number of entrants in period 2, $K_2(1 - H(s_2^2))$, was less than the number of entrants in period 1, $K_1(1 - H(s_1^1))$. Thus, the number of firms could rise initially even if the number of entrants fell.

Intuitively, over time price falls, the more innovative incumbents expand, and the less innovative incumbents exit and are replaced by more innovative, smaller entrants. This can result in a rise in the number of producers. However, as incumbents continue to grow their advantages eventually become insurmountable and entry ceases. Exit continues, though, as the largest firms with the greatest innovative expertise expand their market share and push the less fit firms out of the market. Consequently, eventually the number of firms declines over time.

Consider next the third regularity regarding how the market shares of the leaders change over time. Proposition 3 indicates that the rate of change of the market shares of all incumbents must eventually slow.

PROPOSITION 3: *As each firm grows large, eventually the change in its market share, $\Delta q_{it}/Q_t$, will decline over time.*

PROOF:

Given that Q_t is nondecreasing over time, $\Delta q_{it}/Q_t$ will decline over time if Δq_{it} declines over time. Equation (5) indicates that Δq_{it} is based on the firm's profit margin on the standard product, $p_t - c + l(\text{rc}_{it})$. For incumbents that remain in the industry, rc_{it} will grow over time, causing $l(\text{rc}_{it})$ to grow. Eventually, though, $l(\text{rc}_{it})$ will asymptotically approach its upper bound, and the rise in $l(\text{rc}_{it})$ will approach zero. In contrast, Lemma 5 indicates that p_t will fall in every period to accommodate the desires of incumbents to expand. Therefore, for incumbents that remain in the industry, $p_t - c + l(\mathrm{rc}_{it})$ will eventually decline, causing the increase in their market share, $\Delta q_{it}/Q_t$, to decline.

Intuitively, in every period incumbents expand. The rate at which they expand depends on their profit margin on the standard product. With the marginal product of process R&D eventually approaching zero, all firms eventually experience a decline in their profit margin. This will induce them to decrease the rate at which they expand their market share. Since the largest firms perform the most process R&D, they will be the first to decrease the rate at which they expand their market share. Subsequently, smaller firms will follow.[13]

The other three regularities pertain to the nature of innovation over the PLC. Regarding first the trend over time in the rate of product innovation, it is straightforward to establish the following.

PROPOSITION 4: *After entry ceases, the expected number of product innovations of all firms,* $\Sigma_{i,t}\,(s_i + g(\mathrm{rd}_{it}))$, *declines over time.*

PROOF:

Since $\mathrm{rd}_{it} = \mathrm{rd}^*$ for all firms according to Lemma 1, $s_i + g(\mathrm{rd}_{it})$ remains the same for any firm i that remains in the market. Consequently, once entry ceases, $\Sigma_{i,t}(s_i + g(\mathrm{rd}_{it}))$ declines over time as the number of firms falls.

Proposition 4 explains the eventual decline in the rate of product innovation in new industries reflected in the fourth regularity. Since each firm performs a constant amount of product innovation over time, once entry ceases and the number of firms declines then the expected number of product innovations must decline. Corresponding to this is a decline in the number of distinctive variants of the product for sale. This explains the other part of the fourth regularity concerning the decline in the number of competing versions of the product that eventually occurs in new industries. Note that prior to the shakeout in the number of producers, the number of firms increases over time as more innovative entrants displace larger, less innovative incumbents. This causes the number of competing versions of the product to rise over time. Thus, initially the market induces a rise in the diversity of competing product versions, which eventually gives way to a steady decline in this diversity. In this sense, the emergence of a "dominant design" for a product can be interpreted as the result rather than the cause of the shakeout in the number of producers. In effect, the private benefits of large size eventually compromise the diversity of competing product versions in the market. Since all product innovations are introduced in competing versions of the product and subsequently incorporated into the standard product, over time the rate of product innovation in the standard product will also decline as the number of firms falls.

Consider next the trend over time in the effort devoted to process and product R&D. It is easy to establish the following.

PROPOSITION 5: *For each firm i that remains in the market in period t,* $\mathrm{rc}_{it}/\mathrm{rd}_{it} > \mathrm{rc}_{it-1}/\mathrm{rd}_{it-1}$.

PROOF:

For each firm, Lemma 1 indicates rd_{it} is constant over time and Lemma 4 indicates that rc_{it} rises over time. Hence $\mathrm{rc}_{it}/\mathrm{rd}_{it}$ must rise over time.

[13] Note, though, that there is nothing in the model to ensure that the largest firms remain in the market in every period. Exit will occur in every period, and there is nothing in the model to rule out exit from the first cohort, which contains the largest firms. Nonetheless, it is possible to establish that the largest cohorts will be subject to the lowest rate of exit in the following sense. In each cohort that experiences exit, the firms with the least innovative expertise will exit. Eventually, whole entry cohorts become extinct. This will occur for entry cohort k when s_t^k, the minimum innovation expertise required for survival, exceeds $s_{\max}$. Based on Lemma 8, s_t^k will exceed $s_{\max}$ first for the youngest cohorts, which always have the greatest minimum product-innovation expertise. Thus, once entry ceases the youngest cohorts, which are also the smallest, will experience the greatest rates of exit. This accords with the findings of numerous studies (for example, David S. Evans, 1987; Timothy Dunne et al., 1989).

Proposition 5 establishes that over time every firm that remains in the market increases its effort on process relative to product R&D, which explains the fifth regularity. Intuitively, since the returns to product R&D are independent of firm size while the returns to process R&D are a direct function of firm size, as firms grow they increase their effort on process relative to product R&D. This is just an extreme case of the general idea that the returns to product R&D are less dependent on the output of the firm (prior to the R&D) than the returns to process R&D. In this sense process and product R&D, which are often collapsed into one based on an appeal to a Lancasterian attributes framework, are different.

Proposition 5 applies to individual firms. Eventually the trends at the firm level must also be mirrored at the market level. Once entry ceases, the smallest firms are disproportionately driven from the market given their cost disadvantage. These firms have the highest ratio of product to process R&D because they conduct the least amount of process R&D. Thus, as they disproportionately exit and incumbents increase their level of process relative to product R&D, the ratio of total process to total product R&D for all firms rises.[14] Note, though, that once entry ceases the total process R&D of all firms might decline over time, just at a slower rate than the decline in total product R&D.[15]

The last regularity concerning innovation is that entrants tend to account for a disproportionate share of product innovations relative to incumbents. Let $i_t^k = \Sigma_{i,t}(s_i + g(\text{rd}_{it}))/N_t^k$ denote the expected number of innovations per firm in period t of firms that entered in period k, where N_t^k is the number of firms in period t that entered in period k and the summation is over these firms. Proposition 6 indicates that i_t^k must be greater the younger the cohort.

PROPOSITION 6: *For all periods t, $i_t^k < i_t^l$ for $k < l$.*

PROOF:

Since all firms spend the same amount on product R&D, the expected number of innovations per firm, $s_i + g(\text{rd}_{it})$, is determined exclusively by s_i. This implies that on average the expected number of innovations per firm in each entry cohort will be determined by the average innovative expertise of firms in the cohort. For each period t, Lemma 8 indicates that the minimum innovative expertise of cohort k, s_t^k, is greater the younger the cohort (that is, the larger k). Therefore, the average value of s_i will be greater the younger the cohort, hence $i_t^k < i_t^l$ for $k < l$.

Proposition 6 implies that entrants will be more innovative on average than incumbents, which explains the last regularity. Intuitively, the most recent entrants are smaller than all other firms and thus earn the least profits from the standard product. The only way they survive given this disadvantage is if they are more innovative on average than incumbents. Thus, it is not necessary to appeal to some kind of disadvantage of size in innovation, or to entrants having a greater incentive than incumbents to innovate because they have less to protect (compare Reinganum, 1983, 1985), to explain the greater innovativeness of entrants. Rather, the greater innovativeness of entrants may be attributable to the selection process governing the evolution of the market coupled with an advantage of large firm size in appropriating the returns from R&D. Indeed, if incumbents either had strategic disincentives to innovate or were less efficient at innovation because of their larger size, then opportunities for profitable entry would persist over time, which is not consistent with the first regularity concerning entry eventually becoming small.

[14] Prior to entry ceasing, there is a counteracting force at the level of the market to the trend in the ratio of firm process to product R&D: smaller, more innovative entrants displace larger, less innovative incumbents. Because the entrants are smaller, they have a higher ratio of product to process R&D than the incumbents, which contributes toward a higher ratio of product to process R&D at the market level. Thus, it is possible that prior to entry ceasing, the ratio of process to product R&D at the market level might fall over time. Once entry ceases, however, the ratio must rise.

[15] Whether the total amount of process R&D of all firms declines over time depends on the rate at which incumbent firms expand their process R&D relative to the rate of firm exit, which is not determined within the model.

V. Cross-Sectional Implications of the Model

In this section it is shown that the model can explain various cross-sectional regularities regarding how within industries R&D effort, R&D productivity, cost, and profitability differ across firms according to their size. Since the model was not set up to explain these regularities, its ability to explain them can be viewed as support for its account of the PLC.

A simple cross-sectional implication of the model is that larger firms should perform more total R&D and also devote a greater fraction of their R&D to process innovation.

PROPOSITION 7: *For each period t, the larger the output of the firm at the start of the period, Q_{it-1}, then the greater its total spending on R&D,* $rd_{it} + rc_{it}$, *and the greater the fraction of its total R&D devoted to process innovation,* $rc_{it}/(rd_{it} + rc_{it})$.

PROOF:

This follows directly from Lemmas 1 and 3.

There have been numerous studies of the relationship between total R&D spending and contemporaneous firm size. It has been repeatedly found that R&D and contemporaneous firm size are closely related, with firm size explaining over 50 percent of the variation in firm R&D in more R&D-intensive industries (see Cohen and Klepper [1996b] for a review of these studies). In terms of the composition of firm R&D, F. M. Scherer (1991) analyzes the patents issued to firms in the Federal Trade Commission Line of Business Program in the 10-month period from June 1976 to March 1977. Assigning these patents to business units and classifying them according to whether they are process or product patents, Scherer finds that among business units with patents, the fraction of patents that are process increases with the sales of the business unit. Based on the assumption that the returns to process R&D are more closely tied to the size of the firm than the returns to product R&D, Cohen and Klepper (1996a) develop additional predictions at the level of the industry about the relationship between the fraction of patents that are process and business unit sales. Using Scherer's data, they find support for Proposition 7 at the level of the industry as well as for their more detailed predictions.

The intuition behind Proposition 7 is simple: the larger the firm then the greater the returns from process R&D, hence the greater the effort devoted to R&D in general and process in particular. Alternatively stated, the larger the firm then the greater the output over which it can average the fixed costs of (process) R&D, hence the greater its R&D effort. This implies that the close relationship between R&D and firm size is indicative of an advantage of size. In contrast, most studies have interpreted the close relationship to indicate no advantage of size. They note that R&D does not tend to rise more than proportionally with firm size, which implies that increasing the average firm size would not increase total industry R&D spending. This has been widely interpreted to imply there are no advantages of large firm size in R&D (William L. Baldwin and John T. Scott, 1987 p. 111). But as Cohen and Klepper (1996b) emphasize, without such an advantage it is difficult to explain why there is a close relationship between R&D and firm size.[16]

In addition to predictions about R&D effort and firm size, the model has distinctive implications about how firm size and R&D productivity are related.

PROPOSITION 8: *For each period t, the average product of process R&D,* $l(rc_{it})/rc_{it}$, *and the average product of product R&D,* $(s_i + g(rd_{it}))/rd_{it}$, *vary inversely with the size of the firm,* Q_{it}.

[16] Note that in the model there is no innate advantage of firm size in R&D, as Cohen and Klepper (1996b) point out in a related setting. The advantage of large firm size stems from the inability of firms to sell their innovations in disembodied form and the costliness of rapid growth. In the absence of these restrictions, successful innovations could be embodied in the entire industry output through the sale of the innovations and/or the expansion of successful innovators, and the contemporaneous size of the firm would have no bearing on the firm's incentives to conduct R&D. While many other models assume, either implicitly or explicitly, that innovations cannot be sold and thus link the returns to innovation to the size of the innovator, few assume any restrictions on firm growth.

PROOF:

Given that $l''(\mathrm{rc}_{it}) < 0$ for all rc_{it}, the larger rc_{it} then the lower will be $l(\mathrm{rc}_{it})/\mathrm{rc}_{it}$. In each period t, the larger the firm then the greater its spending on process R&D. Therefore, $l(\mathrm{rc}_{it})/\mathrm{rc}_{it}$ will vary inversely with Q_{it}. Regarding product R&D, Proposition 6 indicates that the expected number of innovations per firm is greater for smaller firms. Since all firms spend the same amount on product R&D, this implies that $(s_i + g(\mathrm{rd}_{it}))/\mathrm{rd}_{it}$ must be inversely related to the size of the firm, Q_{it}.

Proposition 8 is consistent with the findings of studies that examine the relationship between total R&D effort and the number of patents and/or innovations per unit of R&D. John Bound et al. (1984) find that for publicly traded firms, the number of patents per dollar of R&D is considerably greater for firms with smaller R&D budgets. Examining this relationship within industries using data from a comprehensive census of innovations in 1982 conducted for the Small Business Administration, Zoltan J. Acs and David B. Audretsch (1991) generally find an inverse relationship across firms between the number of innovations per dollar of R&D and total R&D spending. If in addition total R&D spending does not rise more than proportionally with firm size within industries, as has generally been found, then Proposition 8 further implies that the total product of R&D will not rise in proportion to firm size. Equivalently stated, within industries larger firms will account for a disproportionately small share of process and product innovations relative to their size. This is consistent with Acs and Audretsch's findings (1988, 1991) based on the Small Business Administration data, especially for more R&D intensive industries, with Scherer's (1965) findings concerning the rate of patenting among large firms, and with the observations of Alice Patricia White (1983) for the select group of dominant firms she analyzes.

This interpretation runs counter to the conventional interpretation of the inverse relationship between R&D productivity and firm size. This finding has been widely interpreted as a further sign of the lack of an advantage of firm size in R&D (see, for example, Acs and Audretsch, 1991). Not only do large firms not spend disproportionately more on R&D than smaller firms, but they appear to get less out of their R&D spending than smaller firms, suggesting they are actually less efficient at R&D than their smaller counterparts. This interpretation, though, raises more questions than it answers. If larger firms are less efficient at R&D, why do they conduct more R&D than smaller firms? Even more fundamentally, how are large firms able to survive and prosper in R&D intensive industries if they are less efficient at R&D than smaller firms?

These questions are readily answered by the model. All firms have the same R&D productivity in the model in the sense that the functions $g(\mathrm{rd}_{it})$ and $l(\mathrm{rc}_{it})$, which calibrate the productivity of product and process R&D respectively, are the same for all firms. The lower average productivity of both product and process R&D in larger firms is a reflection of the competitive advantages conferred by firm size. By applying their (process) R&D to a larger level of output, larger firms are able to appropriate a greater fraction of the value of their (process) R&D than smaller firms. This induces them to undertake more process R&D than smaller firms. Given the diminishing returns to R&D, by undertaking more process R&D larger firms march further down the marginal-product schedule of process R&D, causing the average product of their process R&D to be lower than in smaller firms. At the same time, by undertaking more process R&D and getting a larger return from their process R&D than smaller firms, they earn greater profits from process R&D than smaller firms. This is why they prosper despite the lower average productivity of their R&D than smaller firms. The greater profits they earn from process R&D also enables them to survive with less average product-innovation expertise than smaller firms, which explains why they generate fewer product innovations per dollar of product R&D than smaller firms.[17]

[17] Richard J. Rosen (1991) recently proposed an alternative explanation for why large firms account for a disproportionately small share of innovations relative to their sales which also relies on large size conferring an advantage in appropriating the returns from R&D. His explanation, however, also relies on a stylized depiction of the

The model has further implications regarding how the advantages conferred by size in R&D will be reflected in firm cost and profitability. It predicts that larger firms will have lower average cost.

PROPOSITION 9: *For each period t, firm average cost $c - l(\text{rc}_{it})$ varies inversely with Q_{it}.*

PROOF:

Since rc_{it} varies directly with Q_{it} and $l'(\text{rc}_{it}) > 0$ for all rc_{it}, it follows directly that $c - l(\text{rc}_{it})$ varies inversely with Q_{it}.

This prediction is consistent with the findings of Richard E. Caves and David R. Barton (1990), who use plant data from the Census of Manufacturers to estimate production functions for 4-digit SIC manufacturing industries. Allowing productivity to differ across plants, they find that for the average industry larger plants are more productive than smaller plants. In light of the high correlation between plant and business size, this finding is supportive of Proposition 9. Consistent with the role of R&D in the model in imparting a lower cost to larger firms, Caves and Barton (p. 126) find the relationship between productivity and plant size to be stronger in more R&D intensive industries. Proposition 9 is also consistent with E. Ralph Biggadike's (1979 pp. 65–66) findings about entrants. Using detailed data on new business units of a subset of firms in the PIMS data set, Biggadike finds that entrants tend to start with a pronounced production-cost disadvantage that declines over time as the entrants capture a larger share of the market.

The model has further implications regarding how the advantages conferred by firm size in R&D will be reflected in firm cost and profitability.

PROPOSITION 10: *The largest and most profitable firms will come from the first cohort of entrants. These firms will increase their market shares over time and consistently earn supernormal profits.*

PROOF:

Firms that entered in period 1 with innovative expertise $s_{\max}$ will always be larger than all subsequent entrants and will earn greater profits than all other firms. Consequently, they will consistently earn supernormal profits and will never exit. Since $\Delta q_{it} > 0$ for all incumbents, over time these firms will also increase their market shares.

Proposition 10 implies that the market shares of the largest and most profitable firms in the industry will not decline over time. Furthermore, although the profits of these firms may decline over time as price falls, they will consistently earn supernormal profits. These predictions are consistent with Mueller's (1986) findings concerning the persistence of market share and profitability among the largest manufacturing firms over the period 1950–1972. Mueller finds that a number of these firms maintained their market shares over this 22-year period. While the average profitability of these firms declined over time, they were still earning supernormal returns on investment in 1972. Consistent with the role played by R&D in the model in conferring an advantage to larger firms, Mueller finds that the persistence of market share and profitability was stronger for firms in more R&D-intensive industries. Proposition 10 also predicts that the most successful and long-lived firms will disproportionately come from the earliest entry cohorts. This is consistent with the findings of Klepper and Simons (1993) concerning four products that experienced sharp shakeouts: autos, tires, televisions, and penicillin. They find that the chances of surviving at least 10 years were significantly greater for the earliest entrants, particularly in autos and tires, and that on average the largest firms entered earlier.

In summary, the cross-sectional regularities indicate that the larger the firm then the greater its spending on R&D, the greater the fraction of its R&D devoted to process innovation, the smaller the number of patents and innovations

returns to risky R&D projects which suggests, counter to the evidence assembled in Mansfield (1981), that large firms will account for a disproportionately small share of riskier R&D. As the model indicates, as long as R&D is subject to diminishing returns and large firm size provides an advantage in appropriating the returns to R&D, there is little need to resort to other stylizations to account for the disproportionately small number of innovations accounted for by larger firms.

it generates per dollar of R&D, and the lower its average costs. Furthermore, earlier entrants tend to grow larger and survive longer. Since all of these patterns are predicted by the model, they provide support for it. The extent of the support, though, depends on the degree to which these same patterns can be explained by other theories, particularly theories that can account for various features of the PLC. The most relevant alternative theories are the dominant design view reviewed in the introduction (compare Utterback and Suárez, 1993), which explains many features of the PLC, and theories recently advanced in Jovanovic and MacDonald (1994) and Hopenhayn (1993) to explain shakeouts.

Each of these theories posits technology-based mechanisms which increase exit and/or make entry harder, contributing to a shakeout. In Utterback and Suárez (1993) the mechanism is a dominant design, which leads to exit of firms less able to manage the production process for the dominant design. In Jovanovic and MacDonald (1994) it is a major (exogenous) technological change which leads to exit of firms that are unable to innovate in the new regime. In Hopenhayn (1993) it is a slowdown in product innovation that favors firms that invest in process innovation, in the manner of the dominant design theory.[18]

While the theories do not directly address the cross-sectional regularities, they can nonetheless be used to speak to them. In each theory, the firms that prosper and remain in the industry during the shakeout are the better innovators. It might be expected these firms would spend more on R&D, particularly process R&D in the Utterback and Suárez (1993) and Hopenhayn (1993) models, have lower costs, and grow to be larger. This could explain the cross-sectional regularities involving firm size and total R&D, the fraction of R&D devoted to process innovation, and average cost. The other two regularities, however, are more difficult for the alternative theories to explain. If larger firms are better innovators, they might be expected to generate at least as many, if not more, innovations per dollar of R&D than the smaller firms. Yet the cross-sectional regularities indicate that the number of patents and innovations per dollar of R&D declines with firm size. In terms of the significance of early entry, none of the theories emphasizes the importance of entry timing in conditioning the length of survival of firms that entered prior to the shakeout.[19] Yet the cross-sectional regularities indicate that among products experiencing sharp shakeouts, the date of entry was an important determinant of the length of survival for the preshakeout entrants.[20]

Thus, the alternative theories cannot readily explain all the regularities. This does not imply that the forces they feature are not operative. Indeed, these forces are largely complementary to the ones featured in the model. Judging from the cross-sectional regularities, however, the model appears to capture important forces that are not present in the other theories.

VI. Implications and Extensions

The notion that entry, exit, market structure, and innovation follow a common pattern for new products has become part of the folklore of a number of disciplines, including economics. Although the features of this pattern are based on a limited number of products and much of the evidence is impressionistic, they appear to resonate with our experience. Despite its popularity, though, there are many skeptics about the PLC, both in terms of its logic and its universality. The principal purpose of this paper was to shore up its logical

[18] Hopenhayn (1993) also posits other, nontechnology-based mechanisms that could trigger a shakeout. These are not considered because they cannot address the cross-sectional regularities involving R&D.

[19] In each theory the shakeout is triggered by events which change the basis for competition among incumbents, which if anything might be expected to undermine the value of prior experience.

[20] Moreover, it does not appear to be the shakeout itself which accounts for this effect. Klepper (1996) finds that differences in survival rates for the preshakeout entrants were most pronounced when they were older and had survived a number of years of the shakeout. In the model, this can be explained by the selection process (compare Klepper, 1996). On average, later entrants are better innovators. At young ages, this can offset the disadvantage of late entry for firm survival, but as firms age and the selection process continues to operate, eventually later entrants must experience higher hazard rates.

foundations by showing how a simple model could explain all the central features of the PLC.

The proposed model grounds the PLC with two simple forces. One is that the ability to appropriate the returns to process R&D depends centrally on the size of the firm. The other is that firms possess different types of expertise which lead them to pursue different types of product innovations. The advantage of size in process R&D causes firm process R&D to rise over time and eventually puts entrants at such a cost disadvantage that entry is foreclosed. After entry ceases, firms compete on the basis of their size and also their innovative prowess. As firms exit and the number of firms falls, the diversity of product R&D is compromised, causing the number of product innovations and the diversity of competing product variants to decline. The same two forces also explain the relationship within industries between firm size and total R&D spending, relative spending on product and process R&D, the productivity of R&D, average cost, and profitability. The ability of the model to explain these cross-sectional regularities in addition to the temporal patterns that define the PLC provides support for its explanation of the PLC. It also lends credence to the PLC as a leading case that captures the salient features of the evolution of technologically progressive industries.

A number of stylizations were invoked to highlight the two key forces featured in the model. Perhaps the most noteworthy were the assumptions that average cost was a function of only contemporaneous process R&D, decisions were made solely on the basis of short-term profits, and all innovations were ultimately embodied in the industry's standard product. Although relaxing these assumptions would complicate the model, it need not fundamentally alter the ability of the model to explain the PLC. Regarding process innovation, suppose process improvements were allowed to cumulate. If all process improvements were assumed to be costlessly imitated one period after they were introduced, firm differences in average cost would still be a function of only differences in contemporaneous firm spending on process R&D. Firm average costs would equal $c_t - l(rc_{it})$, where c_t reflects the cumulative effect on cost of all past process innovations by all firms. This change would not fundamentally affect the model.[21] Even if cost differences across firms were allowed to cumulate, it would only reinforce the advantages of the largest firms. If firms were allowed to be forward looking, all firms would accelerate the growth in their output to take account of the advantages of size in R&D and accordingly undertake greater process R&D in each period (Klepper, 1992). But given the costs of expanding output, firms would still grow by finite rates in each period and it would still be advantageous to enter earlier. Indeed, the firms that would accelerate the growth in their output the most would be those that expected to survive longest, which would be the firms that entered earliest with the greatest innovative expertise. Thus, allowing firms to be forward looking would not alter the advantages of early entry and greater innovation expertise and thus would not fundamentally alter the model. Finally, suppose some product innovations were not embodied in the standard product but formed the basis for separate product niches. If all permanent product variants could be costlessly imitated one period after they were developed and process innovation lowered the average cost of all product variants, then the implications of the model would not change. All firms would produce all product variants and the incentives for process R&D would depend on the total output of all variants.[22]

The depiction in the model of how market structure and performance evolve over time for new products is different from the conventional industrial organization paradigm on structure and performance. Historically, industry characteristics were seen as shaping the nature of firm cost functions and barriers to entry, which in turn determined structure and performance. With few exceptions, firm differences within industries were thought to be

[21] The only implication of the model that would change is Proposition 3, which would require further structuring of the model to establish.

[22] The only way the model would be fundamentally altered is if each product niche required its own process R&D. In this case, each product niche would be analogous to a separate industry, and the model would no longer be a model of industry evolution but of industry fragmentation.

irrelevant (Mueller, 1986 pp. 223–24). In recent years, however, it has been recognized that firm differences may be at the root of a number of important phenomena, such as the positive correlation across industries between industry concentration ratios and mean firm profitability (Harold Demsetz, 1973). The model takes this approach a step further by embedding differences in firm capabilities in an evolutionary setting in which expansion in output at any given moment is subject to increasing marginal costs and firm size imparts an advantage in certain types of R&D. The result is a world in which initial firm differences get magnified as size begets size, which imparts an advantage to early entry and leads to an eventual decline in the number of firms and the rate of product innovation.[23]

The starkness of the model precludes any departures from this evolutionary pattern. This can be remedied by allowing for random events that alter the relative standing of incumbents and potential entrants. For example, if cohorts differ in terms of the distribution of their innovative expertise or if the innovative expertise of incumbents is undermined by certain types of technological changes, then later entrants may leapfrog over the industry leaders and the firms that eventually dominate the industry may not come from the earliest cohort of entrants.[24] Some products are described as eventually becoming commodities, which could be accounted for in the model by allowing technological opportunities for innovation eventually to dry up. Incumbent firm product and process R&D would then eventually decline to zero and the advantages of early entry would eventually be eliminated, allowing the number of firms to stabilize before the shakeout of producers had run its full course. The model could also be generalized to include other activities, such as marketing and advertising, that could substitute for process R&D in imparting an advantage to larger firms (Sutton, 1991).[25] While these generalizations would no doubt enrich the model and allow it to accommodate departures from the PLC that have been observed in some technologically progressive industries (compare Klepper, 1992), even in its stark form the model is able to address a wide range of regularities. It demonstrates that many aspects of industry evolution and heterogeneity within industries in firm R&D effort and profitability can be explained by coupling random differences in firm capabilities with advantages of firm size conferred by R&D.

[23] The welfare implications of these and other predictions of the model are developed in Klepper (1992).

[24] These and other generalizations of the model are analyzed in Klepper (1992).

[25] Indeed, for some industries even product R&D could play this role, although it would seem as if firm size plays a more important role in conditioning the returns to process than product R&D. This issue, and others, such as why firms are limited in their ability to control their innovation expertise, involve key aspects of the model that merit further study.

REFERENCES

Abernathy, William J. *The productivity dilemma.* Baltimore: The Johns Hopkins University Press, 1978.

Abernathy, William J.; Clark, Kim B. and Kantrow, Alan M. *Industrial renaissance: Producing a competitive future for America.* New York: Basic Books, 1983.

Abernathy, William J. and Utterback, James M. ''Patterns of Industrial Innovation.'' *Technology Review,* June/July 1978, 80, pp. 41–47.

Acs, Zoltan J. and Audretsch, David B. ''Innovation in Large and Small Firms.'' *American Economic Review,* September 1988, *78*(4), pp. 678–90.

______. ''R&D, Firm Size, and Innovative Activity,'' in Zoltan J. Acs and David B. Audretsch, eds., *Innovation and technological change: An international comparison.* New York: Harvester Wheatseaf, 1991, pp. 39–59.

Aitken, Hugh G. J. *The continuous wave: Technology and American radio, 1900–1932.* Princeton, NJ: Princeton University Press, 1985.

Anderson, Philip and Tushman, Michael L. ''Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change.'' *Administrative Science Quarterly,* December 1990, *35*(4), 604–33.

Baldwin, William L. and Scott, John T. *Market structure and technological change.* Chur, Switzerland: Harwood Academic Publishers, 1987.

Biggadike, E. Ralph. *Corporate diversification: Entry strategy and performance.* Cambridge, MA: Harvard University Press, 1979.

Bound, John; Cummins, Clint; Griliches, Zvi; Hall, Bronwyn H. and Jaffe, Adam. "Who Does R&D and Who Patents?" in Zvi Griliches, ed., *R&D, patents, and productivity.* Chicago: University of Chicago Press for the National Bureau of Economic Research, 1984, pp. 21–54.

Bright, Arthur A. *The electric lamp industry.* New York: Macmillan, 1949.

Bright, James R. *Automation and management.* Boston: Graduate School of Business Administration, Harvard University, 1958.

Caves, Richard E. and Barton, David R. *Efficiency in U.S. manufacturing industries.* Cambridge, MA: MIT Press, 1990.

Clark, Kim B. "The Interaction of Design Hierarchies and Market Concepts in Technological Evolution." *Research Policy,* October 1985, *14*(5), pp. 235–51.

Cohen, Wesley M. and Klepper, Steven. "The Anatomy of Industry R&D Intensity Distributions." *American Economic Review,* September 1992, *82*(4), pp. 773–99.

______. "Firm Size and the Nature of Innovation within Industries: The Case of Process and Product R&D." *Review of Economics and Statistics,* 1996a.

______. "A Reprise of Size and R&D." *Economic Journal,* forthcoming 1996b.

Dasgupta, Partha and Stiglitz, Joseph. "Industrial Structure and the Nature of Innovative Activity." *Economic Journal,* June 1980, *90*(358), pp. 266–93.

De Bresson, C. and Townsend, J. "Multivariate Models for Innovation: Looking at the Abernathy-Utterback Model with Other Data." *Omega,* 1981, *9*(4), pp. 429–36.

Demsetz, Harold. "Industry Structure, Market Rivalry, and Public Policy." *Journal of Law and Economics,* April 1973, *16*(1), pp. 1–9.

Drew, Philip G. "Despite Shakeout, Imaging Industry Not Doomed to Being Greek Tragedy." *Diagnostic Imaging,* November 1987, 9, pp. 95–99.

Dunne, Timothy; Roberts, Mark J. and Samuelson, Larry. "The Growth and Failure of U.S. Manufacturing Plants." *Quarterly Journal of Economics,* November 1989, *104*(4), pp. 671–98.

Evans, David S. "Tests of Alternative Theories of Firm Growth." *Journal of Political Economy,* August 1987, *95*(4), pp. 657–74.

Flaherty, M. Therese. "Industry Structure and Cost-Reducing Investment." *Econometrica,* July 1980, *48*(5), pp. 1187–209.

Flamm, Kenneth. *Creating the computer.* Washington, DC: The Brookings Institution, 1988.

Gilbert, Richard J. and Newbery, David M. G. "Preemptive Patenting and the Persistence of Monopoly." *American Economic Review,* June 1982, *72*(3), pp. 514–26.

Gort, Michael and Klepper, Steven. "Time Paths in the Diffusion of Product Innovations." *Economic Journal,* September 1982, *92*(367), pp. 630–53.

Hollander, Samuel. *The sources of increased efficiency: A study of Du Pont rayon plants.* Cambridge, MA: MIT Press, 1965.

Hopenhayn, Hugo A. "The Shakeout." Working Paper No. 33, Universitat Pompeu Fabra, 1993.

Hounshell, David A. "The Making of the Synthetic Fiber Industry in the United States." Mimeo, Harvard Business School, 1988.

Jovanovic, Boyan. "Selection and the Evolution of Industry." *Econometrica,* May 1982, *50*(3), pp. 649–70.

Jovanovic, Boyan and MacDonald, Glenn H. "The Life Cycle of a Competitive Industry." *Journal of Political Economy,* April 1994, *102*(2), pp. 322–47.

Klein, Burton H. *Dynamic economics.* Cambridge, MA: Harvard University Press, 1977.

Klepper, Steven. "Entry, Exit, and Innovation over the Product Life Cycle: The Dynamics of First Mover Advantages, Declining Product Innovation, and Market Failure." Mimeo, Carnegie Mellon University, 1992.

______. "Evolution, Market Concentration, and Firm Survival." Mimeo, Carnegie Mellon University, 1996.

Klepper, Steven and Graddy, Elizabeth. "The Evolution of New Industries and the Determinants of Market Structure.'' *Rand Journal of Economics,* Spring 1990, *21*(1), pp. 27–44.

Klepper, Steven and Simons, Kenneth L. ''Technological Change and Industry Shakeouts.'' Mimeo, Carnegie Mellon University, 1993.

Kraus, Jerome. ''An Economic Study of the U.S. Semiconductor Industry.'' Ph.D. Dissertation, New School for Social Research, 1973.

Mansfield, Edwin. ''Entry, Gibrat's Law, Innovation and the Growth of Firms.'' *American Economic Review,* December 1962, *52*(5), pp. 1031–51.

______. ''Composition of R and D Expenditures: Relationship to Size of Firm, Concentration, and Innovative Output.'' *Review of Economics and Statistics,* November 1981, *63*(4), pp. 610–15.

Mowery, David C. and Rosenberg, Nathan. *Inside the black box: Technology and economics.* New York: Cambridge University Press, 1982.

Mueller, Dennis C. *Profits in the long run.* Cambridge: Cambridge University Press, 1986.

Mueller, Dennis C. and Tilton, John. ''Research and Development Costs as a Barrier to Entry.'' *Canadian Journal of Economics,* November 1969, *2*(4), pp. 570–79.

Nelson, Richard R. ''Assessing Private Enterprise: An Exegesis of Tangled Doctrine.'' *Bell Journal of Economics,* Spring 1981, *12*(1), pp. 93–111.

Nelson, Richard R. and Winter, Sidney G. ''Forces Generating and Limiting Concentration under Schumpeterian Competition.'' *Bell Journal of Economics,* Autumn 1978, *9*(2), pp. 524–48.

______. *An evolutionary theory of economic change.* Cambridge, MA: Harvard University Press, 1982.

Pavitt, K. and Rothwell, R. ''A Comment on 'A Dynamic Model of Process and Product Innovation.' '' *Omega,* 1976, *4*(4), pp. 375–77.

Porter, Michael E. *Competitive strategy.* New York: The Free Press, 1980.

______. ''The Technological Dimension of Competitive Strategy,'' in Richard S. Rosenbloom, ed., *Research on technological innovation, management and policy.* Greenwich, CT: JAI Press, 1983.

Prusa, Thomas J. and Schmitz, James A. ''Are New Firms an Important Source of Innovation?'' *Economics Letters,* March 1991, *35*(3), pp. 339–42.

Reinganum, Jennifer. ''Uncertain Innovation and the Persistence of Monopoly.'' *American Economic Review,* September 1983, *73*(4), pp. 741–48.

______. ''Innovation and Industry Evolution.'' *Quarterly Journal of Economics,* February 1985, *100*(1), pp. 81–99.

Rosen, Richard J. ''Research and Development with Asymmetric Firm Sizes.'' *Rand Journal of Economics,* Autumn 1991, *22*(3), pp. 411–29.

Scherer, F. M. ''Firm Size, Market Structure, Opportunity, and the Output of Patented Inventions.'' *American Economic Review,* December 1965, *55*(5), pp. 1097–125.

______. ''Changing Perspectives on the Firm Size Problem,'' in Zoltan J. Acs and David B. Audretsch, eds., *Innovation and technological change: An international comparison.* New York: Harvester Wheatseaf, 1991, pp. 24–38.

Schmookler, Jacob. *Invention and economic growth.* Cambridge, MA: Harvard University Press, 1966.

Shaked, Avner and Sutton, John. ''Product Differentiation and Industrial Structure.'' *Journal of Industrial Economics,* December 1987, *36*(2), pp. 131–46.

Sutton, John. *Sunk costs and market structure.* Cambridge, MA: MIT Press, 1991.

Tilton, John E. *International diffusion of technology: The case of semiconductors.* Washington, DC: The Brookings Institution, 1971.

Utterback, James M. and Abernathy, William J. ''A Dynamic Model of Process and Product Innovation.'' *Omega,* 1975, *3*(6), pp. 639–56.

Utterback, James M. and Suárez, Fernando F. ''Innovation, Competition, and Industry Structure.'' *Research Policy,* February 1993, *22*(1), pp. 1–21.

von Hippel, Eric. *The sources of innovation.* Oxford: Oxford University Press, 1988.

White, Alice Patricia. *The dominant firm.* Ann Arbor, MI: UMI Research Press, 1983.

Williamson, Oliver E. *Markets and hierarchies: Analysis and antitrust implications.* New York: The Free Press, 1975.