

Demand Heterogeneity and Technology Evolution: Implications for Product and Process Innovation

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The evolution of technology has been a central issue in the strategy and organizations literature. However, the focus of much of this work has been on what is essentially the “supply side” of technical change—the evolution of firm capabilities. We present a demand-based view of technology evolution that is focused on the interaction between technology development and the demand environment in which the technology is ultimately evaluated. We develop a formal computer simulation model that explicitly considers the influence of heterogeneity in market demand—the presence of consumers with different needs and requirements—on firms’ innovation choices. The model is used to examine the dynamics of product and process innovation (Utterback and Abernathy 1975). The analysis reveals that demand heterogeneity offers an alternative to supply-side explanations of the technology life cycle. Further, by considering the implications of decreasing marginal utility from performance improvements, the model highlights the role of “technologically satisfied” consumers in shaping innovation incentives, and suggests a rationale for a new stage in the technology life cycle characterized by increasing performance at a stable price. The stage has not yet been treated formally in the literature, but is widely observed, most prominently in digital and information-based technologies.

(Technology Life Cycle; Price Evolution; Demand Heterogeneity)

1. Introduction

The challenge of understanding the dynamics of technological development has long been a concern of the management field. Two dominant approaches inform the discussion of technological change: One suggests that innovation is driven by the external requirements of the market (Schmookler 1966), while the other views the activities and internal capabilities of firms as the primary drivers of innovation (Dosi 1982). Taken in isolation, each approach highlights key aspects of technological development but, as many have argued, the greatest insight derives from their joint consideration (Mowery and Rosenberg 1979).

Despite this call for balance, by far the larger portion of work on technological change is concentrated on the “supply-side” dynamics—whether at the macro level of technological trajectories (Dosi 1982, Sahal 1985) or the path dependent nature of individual firm capabilities (Helfat 1996). Relatively underexplored in these discussions of innovation is the effect of the demand environment on the development and evolution of technology (though see Clark 1985, von Hippel 1988, Christensen 1997, Malerba et al. 1999 for important exceptions). Technical developments are a function of the opportunity structure that firms perceive. This opportunity structure, in turn, is a function of the firm’s current set of capabilities (Dosi 1982,

Nelson and Winter 1982, Cohen and Levinthal 1989), the inherent possibilities offered by the alternative technologies (Sahal 1985), and the market context in which the firm operates (Christensen 1997).

We develop a demand-based view of technology evolution that is focused on the interaction between technology development *and* the demand environment in which the technology is ultimately evaluated. A critical element in our framework is the inherent diversity that underlies the notion of "market" demand. The latent set of consumers may have widely differing needs and requirements. We characterize consumers by two attributes: the minimum performance requirements that a product technology must satisfy in order for the consumer to be willing to consider purchasing a good, and the consumer's willingness to pay for product performance. We examine the evolution of a technology whose development is locally constrained, and in turn path dependent, but globally unconstrained regarding the absolute, or asymptotic, limits to its progress.

The model is used to examine the dynamics of product and process development throughout the technology life cycle. Currently, the pattern of product and process innovation is understood as the result of the emergence of dominant designs (Utterback and Abernathy 1978, Anderson and Tushman 1990) and of how appropriability opportunities change with firm size (Klepper 1996). In contrast, we suggest that this pattern may be an outcome of locally adaptive behavior of firms in a heterogeneous demand environment.

In a heterogeneous demand environment, early technological development is motivated by the drive to meet market requirements. Depending on the initial functionality and cost of the technology, this may lead to an early emphasis on product technology to enhance the functionality of the technology in order to meet the demand requirements of users, or on process technology to reduce the price to a level that corresponds to consumers' willingness to pay. In later stages of development, when the technology has surpassed market requirements, technical developments are driven by the desires of competitive firms to maximize their profits in the face of "technologically satisfied" consumers.

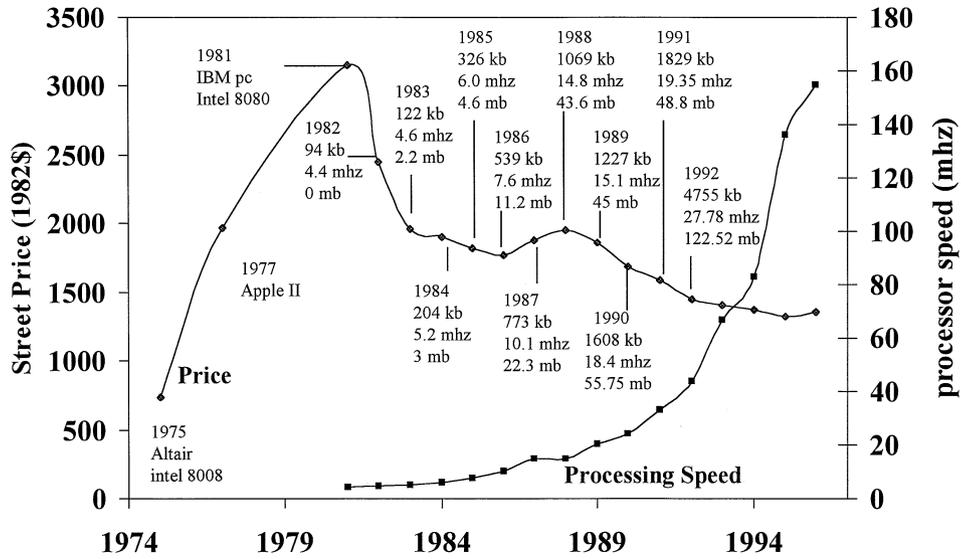
This latter stage of development suggested by the model implies the existence of a new stage in the technology life cycle characterized by increasing performance at a relatively stable product price. This stage has not yet been treated in the literature, but is increasingly evident, most prominently in electronic-based technologies. For example, firms drawing from electronic-based technologies benefit from the biannual doubling of performance predicted by Moore's Law (The Economist 1997). As a result, firms' technology management challenge shifts from the focused pursuit of performance improvement to include the ways in which these improvements are valued and applied by their customers. In settings in which the rate of technological improvement outpaces the demand for this improvement, consumers' marginal utility from performance increases plays a critical role in shaping firms' pricing and development choices.

Consider the price performance histories of videocassette recorders and personal computers shown in Figures 1 and 2. A striking similarity between them is the stability of product price in the later stages of product evolution, even as their objective performance continues to increase. While computing power more than quadrupled between 1992 and 1996, the average unit price for a personal computer remained stable at around \$2,000 throughout the period (Computer Intelligence Info Corp 1996).¹ Similarly, VCR prices remained relatively stable from 1990 to 1997, even as new features were introduced yearly (Consumer Reports 1990-97). Thus, rather than observing price increases that reflect a premium that suppliers can extract for the greater functionality delivered, or stable functionality at decreasing prices, we observe functionality increases at stable prices. Similar histories could be compiled for fax machines, modems, copiers, and numerous other products.

The remainder of the paper is structured as follows. We first explore existing approaches to the technology life cycle and the treatment of market demand in the literature on technology evolution. We then develop the conceptual framework of demand heterogeneity

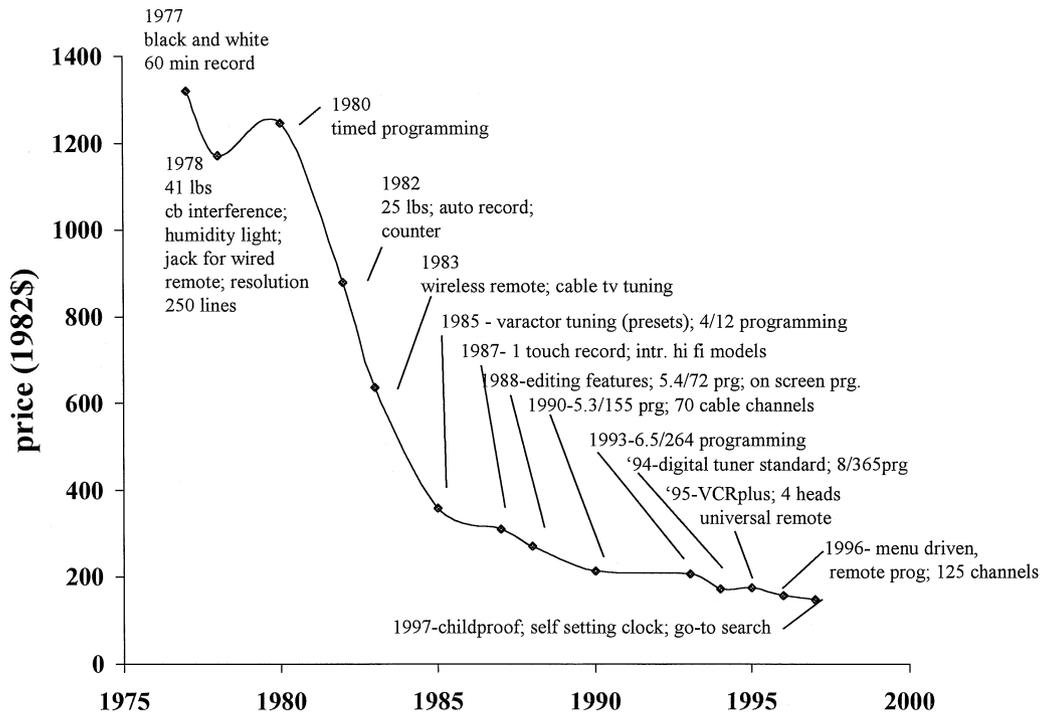
¹ This price has dropped significantly since 1997 with the introduction of \$1,000 desktop computers. The implications of this change for the arguments presented here are discussed later in the paper.

Figure 1 Personal Computers: Prices, Memory, CPU Speed, Hard Drive Capacity



Compiled from a Berndt and Griliches (1993, 1995), industry histories, and publicly reported findings from data from market data firms.

Figure 2 VCR Price History



Compiled from data on models featured in Consumer Reports.

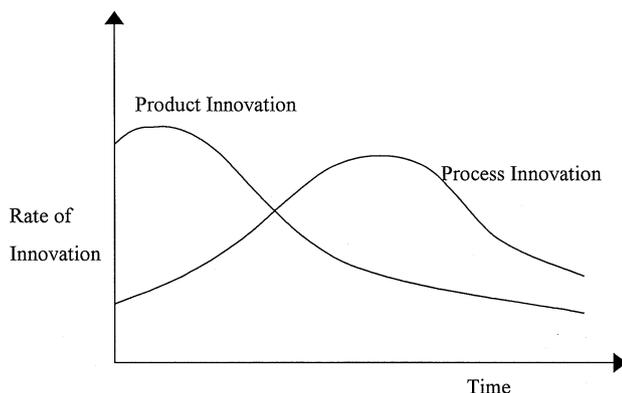
and use this framework as a basis for a formal model of technology development, which we analyze using a computer simulation. We conclude by examining the distinctive implications that derive from a view of technological development that is informed by this more detailed consideration of market demand.

2. Dynamics of Product and Product Innovation

The technology life cycle describes the dynamics of product and process innovation and has long held a central place in the literature on technology management (Meuller and Tilton 1969, Utterback and Abernathy 1975, Clark 1985, Klepper 1996). The pattern that has been widely described is illustrated in Figure 3. Porter (1983, p. 22) provides a succinct summary of the dominant explanation for this behavior:

Initially, ... product design is fluid, and substantial product variety is present. Product innovation is the dominant mode of innovation and aims primarily at improving product performance. Successive product innovations ultimately yield a "dominant design" where the optimal product configuration is reached. Process innovation is initially minor in significance, and early production processes are characterized by small scale, flexibility, and high labor skill levels. As product design stabilizes, increasingly automated production methods are employed and process innovation to lower costs takes over as the dominant innovation mode. Ultimately, innovation of both types begins to slow down.

Figure 3 Dynamics of Product and Process Innovation



From Utterback and Abernathy (1975)

The dominant design approach is primarily focused on the supply side and the reduction of uncertainty that allows for investment in specialized production equipment. While this approach recognizes that consumer requirements influence the establishment of a dominant design, it is silent on the role of demand on postdominant design developments. Several of the assumptions underlying the dominant design explanation are problematic. First is the assumption of a clear ordering between product and process innovation that posits that firms will tend to ignore the production process and control of costs until the product design has been fixed (DeBresson and Townsend 1985). While design improvements are a primary driver of market acceptance, in many instances cost savings provide the critical motivation for technological substitution and are therefore an early focus of innovative effort. A second problem is the assumption of the depletion of product improvement opportunities. The generalizability of claims of diminishing technological opportunities, however, is refuted in several studies that closely examine this issue (e.g. Christensen 1992, Henderson 1995).

An alternative explanation for the technology life cycle (Klepper 1996) suggests that the shift in innovative focus from product to process development is driven by changes in the ability of innovating firms to appropriate returns from their investments in innovation. According to this perspective, the value of process innovation is proportional to the level of output produced by a given firm. Thus, as an industry matures and firms get bigger, firms have increasing incentives to pursue process innovations. In contrast, since returns to product innovations are related to the acquisition of new customers rather than the magnitude of the existing customer base, the relative return to product innovation declines over time.

This scale-appropriability approach predicts the rise of process innovation without placing exogenous limits on opportunities for product innovation or interdependence between innovation regimes. However, it does not address the continued pursuit of product innovation that is exhibited in industries such as consumer electronics and computers, which are dominated by the large firms that would be predicted to

shy away from product innovation. Indeed, in reviewing the patent counts compiled by Gort and Klepper (1982) for over 46 product classes, Klepper himself states that "neither series reflects the decline over time in product innovation conjectured in the PLC [product life cycle]" (1997, 167).

Common to both the dominant design and the scale-appropriability approaches is a focus on the dynamics of supply without an explicit examination of the demand context in which the innovating firm operates. In addition, both sets of arguments imply that product innovation will necessarily precede process innovation, which, while a common pattern, is not a universal one. We develop a finer grained consideration of the demand context and how it can inform our understanding of the evolution of technology in general, and the technology life cycle in particular.

3. Heterogeneity and Markets

To understand the evolution of product technology, we must characterize the nature of the demand environment in which the technology evolves. In particular, if we wish to understand how firms trade off the development of process and product technologies, we must characterize consumers' willingness to pay for enhancements to the product. In addition, a critical element in consumers' preference structure in the context of emerging technologies is the minimum performance threshold that a product must reach if it is to be of value to a given consumer. The focus in this analysis is heterogeneity in this minimum performance threshold among consumers and in consumers' willingness to pay for products that meet this performance threshold.

Thresholds

The notion of heterogeneous thresholds is well established in a variety of literatures including consumer choice (McFadden 1986, Green and Wind 1973) and the diffusion of innovation (Stoneman 1987), and is embodied in the notion of reservation prices in microeconomic models (Varian 1978). The basic notion common to these applications is that the adoption of a technology or the purchase of a good is a

discrete decision that is prompted by some threshold of "attractiveness" being surpassed.

We define a consumer's *functionality threshold* as the minimum objective performance (independent of price) that a given product must deliver in order for the consumer to consider it. Associated with this functionality threshold is a consumer's *net utility threshold* which specifies the highest price that a consumer is willing to pay for a product that just satisfies his or her functionality requirements. The value of considering the two thresholds jointly, rather than combining them both into a single construct, is that it allows for an explicit consideration of technology improvements in both performance and price.

A functionality threshold specifies the performance level below which a consumer will not accept a product, *regardless of its price*. A product that falls below a given consumer's functionality threshold is, for that consumer, "junk" and would not be accepted at any positive price. The same product, however, may well be acceptable to a consumer with a different functionality threshold.

Functionality thresholds are determined, in part, by inherent task requirements and, in part, by context. Thus, a machinist drilling high precision parts cannot make use of a drill press with loose tolerances, no matter how low its selling price, because such a machine is not able to support the intended application. Alternatively, functionality requirements can be externally imposed, by the demands of downstream customers (e.g., producers of goods for the luxury market will need higher quality materials than those producing for the economy market) or by externally imposed regulations (e.g., electricity producers in California require cleaner generating stations than producers North Dakota in order to be certified for operation).

Net utility thresholds capture the interaction of product performance and price. The net utility reflects the highest price a consumer is willing to pay for a product that just meets his or her requirements. Consumers with the same functionality threshold may have different net utility thresholds. Variation in willingness to pay may be driven by differences in budget constraints, but more importantly, particularly in the context of firms, by nonbudgetary differences as well.

Consumers may differ in the value they derive from the product for a number of reasons. Consumers may differ in their ability to exploit the product as a result of heterogeneity in internal resources and capabilities, or human capital. For instance, a skilled programmer may be able to derive more benefit from a given computer system than a less skilled one. Alternatively, differences in net utility thresholds may stem from the scale at which the buyer can apply the product. A firm that can apply the product toward the production of a good that it can then sell to a large downstream customer base would be willing to pay more for the product than a potential buyer with a smaller customer base. Finally, differences in willingness to pay may reflect variation in the availability and presence of a substitute product or service. A firm that has previously invested in a substitute good will benefit from the new product only to the extent that the product provides an improvement relative to the existing substitute; alternatively, a similar firm, not in possession of a substitute, will value the product on the basis of the absolute benefit it provides.

Decreasing Marginal Utility from Performance Improvements

While consumers have a minimum threshold for acceptable performance, there is no analogous boundary that specifies a maximum limit to the functionality that a consumer would be willing to accept. At the same time, it is reasonable to assume that there is decreasing marginal utility to increases in functionality (Meyer and Johnson 1995). Correspondingly, it is reasonable to assume that consumers show a positive, but decreasing, willingness to pay for improvements beyond their requirements.

Thus, as consumer requirements are exceeded, their willingness to pay for improvement will become increasingly small to the point that firms will be unable to extract any meaningful premium for further improvement. However, even if consumers place little value on performance differences at sufficiently high absolute levels of functionality, they will still, all else being equal, choose the more advanced product. As a result, in a competitive context this responsiveness to functionality improvements forces firms to continue to enhance functionality even when such

enhancements have little effect on consumers' willingness to pay.

Dynamics of Technology in Heterogeneous Markets

The presence of different threshold levels for both functionality and net utility implies that consumers will vary in the degree to which a product technology at a given state is capable of satisfying their requirements. In turn, there will be variation in the type, and amount, of development that is required before the product becomes relevant to a given consumer. While models of the diffusion of innovation explicitly consider demand heterogeneity in explaining the differences in adoption rates and decisions, they tend to focus on the diffusion of a fixed innovation (Brown 1981, Rogers 1994), and thus fail to consider the interaction between changes in the innovation that result from further development and consumers' adoption decisions (Rogers 1994, Reingenum 1989).²

In mature markets, functionality and price are often confounded as consumers with high (low) functionality requirements generally buy more (less) expensive products. However, functionality and price need not be coupled. In markets for emerging technologies, potential consumers with a high willingness to pay for the product who have, at the same time, low functionality requirements, play an important role in both the development and adoption of an innovation. For instance, the early market for xerography was comprised of firms that made original master plates for offset printing. Because these firms were able to integrate the machine into a specialized activity, they were able to benefit from the technology at a time when other potential consumers found xerography unacceptably complex and unreliable. It was only after extensive further development that Xerox machines were able to satisfy the much higher functionality demands of the mainstream office market (Dessauer 1971). In such cases, finding consumers who are willing to pay a high price for a relatively

² Those few models that do examine a changing innovation (Stoneman 1987, Jensen 1982) do so in the context of two period models which do not really speak to an evolutionary pattern, and address product changes of only one type (either price decrease or quality improvement) but not both simultaneously.

crude product may be critical to firms' ability to engage in the development effort.

In the context of emerging technologies, firms do not have the option of positioning their product in the attribute-price space at will, but rather need to engage in development to affect product characteristics. This contrasts with the spirit of the classic segment-target-position (STP) marketing paradigm (Kotler 1991), in which firms are told to first segment the market, then examine the characteristics of consumers in these individual segments, and then consider ways of tailoring the product to meet segment specific needs. Such an approach is appropriate when firms can manipulate product attributes at will, as in typical marketing examples of varying sweetness, saltiness, and tartness in a food product.

When the manipulation involves challenging performance attributes that cannot be easily or quickly changed, such as reliability, size, and speed, this tailoring approach becomes less managerially tractable. In such situations, an approach that considers the interaction of consumer needs with both short- and long-term technological possibilities may be more informative. We explore the path-dependent development of technology, where path dependence results from both the "supply-side" constraints of technical change at any moment in time, and the history of feedback from the demand contexts in which the technology has been applied.

4. Model Structure

The model structure has two basic components—a characterization of consumers and consumer preferences that comprises the demand environment, and a mechanism by which products move through this market space. The market space is defined by a functionality dimension and a price dimension. In every period, firms make development decisions that affect the location of the product technology in this space; consumers, in turn, respond to the product offerings by either purchasing or not purchasing a unit quantity of the product.

It is assumed that consumers engage in repeat purchasing behavior in such a way that the entire population of consumers considers making a purchase in

every period and that consumer preferences are stable over time.³ Although preferences are stable, consumer purchase decisions vary as product performance and price vary over time. Consumers are assumed to be well informed,⁴ in that they have accurate information about product performance each period. Firms are assumed to maximize current period profits.⁵

In the model, consumers are characterized by two basic factors. The first factor, F_{i0} , specifies individual i 's minimum functionality requirement. The second factor, U_{i0} , specifies consumer i 's minimum utility requirement, which determines the price, P_{i0} , that consumer i would be willing to pay for a minimally acceptable product. The population of consumers is specified by independently drawing values of F_{i0} and U_{i0} from a uniform distribution of sufficient range that multiple innovation attempts are required to reach all consumers in the market. The functional benefit, B_{ij} , that consumer i derives from product j is determined

³This situation is characteristic of a market for durable goods with regular entry of consumers, such as the entry of some fixed number of new households into an economy every year. Alternatively, this type of repeat purchasing behavior could characterize a fixed population purchasing a nondurable good. The assumption of some sort of continuing purchase, whether through a renewing population of single good purchasers or a fixed population of repeat purchasers, is important to the model in that it is the potential of attracting existing as well as new customers that drives firms to innovate. As a result, a single purchase, fixed population model would not generate the behavior observed in the last phase of the current model because, in effect, such a model stipulates the "end of history" after full penetration. A less extreme model, however, such as one in which goods face obsolescence after some number of periods, would generate incentives for continued innovation on the part of firms as they compete for whichever consumers are active in the market in each period.

⁴The current model makes the simplifying assumption that consumers are perfectly informed regarding product performance. Because the interest is in the qualitative pattern of behavior, consumer uncertainty would be a relevant factor if it were to affect firms' development decisions in a systematic way. With no compelling reason to bias consumers' assessment of product performance in either the positive or negative direction, the error in the assessment would have to be modeled as a symmetric distribution around the true value. Such an error, while affecting the absolute values associated with the observed outcomes, would not affect the qualitative nature of the results.

⁵This can be thought of as price-skimming behavior (Kotler 1991) and is the same assumption made in Klepper (1996).

by the functionality offered by the product in excess of the consumer's minimum functionality threshold:

$$B_i(F_j) = \begin{cases} F_j - F_{oi} + 1 & \text{if } F_j - F_{oi} \geq 0 \\ 0 & \text{otherwise.} \end{cases} \quad (1)$$

The utility, U_{ij} , that consumer i derives from product j is specified as a Cobb-Douglas utility function which trades off price and functionality as⁶

$$U_i(F_j, P_j) = (B_i(F_j))^\alpha (1/P_j)^{1-\alpha}, \quad \text{where } 0 < \alpha < 1. \quad (2)$$

Consumers will reject any product that does not meet both their functionality and utility requirements, such that $B_i \geq 1$, and $U_{ij} \geq U_{i0}$.⁷ Thus, P_{i0} is the highest price a consumer will be willing to pay for a product that just satisfies his or her functionality requirement, (i.e., $B_{ij} = 1$) and is characterized as

$$P_{i0} = (U_{i0})^{1/(\alpha-1)}. \quad (3)$$

As discussed above, consumers value functionality improvements beyond their threshold requirements, $\partial U_{ij}/\partial B_{ij} > 0$, but at a decreasing rate, $\partial^2 U_{ij}/\partial B_{ij}^2 < 0$. This property of diminishing returns to improvements holds for α values below 0.5. From the utility function, we solve for P_{ij} , the maximum price a consumer would be willing to pay for a product that meets his or her functionality requirements, as⁸

$$P_{ij} = P_{i0} (B_i(F_j))^{\alpha/1-\alpha}. \quad (4)$$

Given a choice among a set of acceptable products, a consumer selects the product that maximizes his or her utility. In every period, the entire population of consumers is exposed to the available products and each consumer selects his or her own best choice.

⁶ The model is a monotonic transformation of the utility function of standard vertical differentiation models, where $U = KB - P$ (Tirole 1988) (Note that $[\log U]/(1-\alpha) = (\alpha/(1-\alpha)) \log B - \log P$). The current model differs from the standard model in that it introduces minimum thresholds for functionality and diminishing returns to functional improvements.

⁷ The imposition of a lower bound on utility, U_{i0} , stems from the assumption that consumers have a choice of other products.

⁸ To find P_{ij} we identify the product j such that $U_i(F_j, P_j) = U_{i0}$.

Evolution of Product Technology

Products are represented by their functional performance and by cost of production. Following the characterization used in previous analytical models (Klepper 1996), the effect of product and process innovations is reflected in changes in the product's functional performance and cost.⁹ Product innovation enhances functionality by a fixed amount, F^{prod} , and leads to a fixed production cost increase, C^{prod} . Thus, a product innovation affects product j in the following manner:

$$F_{j,t+1} = F_{j,t} + F^{\text{prod}}, \quad (5)$$

$$C_{j,t+1} = C_{j,t} + C^{\text{prod}}. \quad (6)$$

Process innovation leaves product functionality unchanged, while lowering the cost of production by a constant percentage, Δ_c . Thus, a process innovation affects product j as follows:

$$F_{j,t+1} = F_{j,t}; \quad (7)$$

$$C_{j,t+1} = C_{j,t}(1 - \Delta_c). \quad (8)$$

The geometric decrease in cost due to process innovation has an empirical basis, as discussed in the learning curve literature (Boston Consulting Group 1972).

In reality, the rate of innovative improvement is a function of the resources devoted to innovation, as well as technological possibilities. The S-curve literature (Foster 1986) shows that, at later stages of development, increasingly larger resource investments are required to maintain a constant rate of performance improvement. Often, these investments are justified by the (expected) growth of the market in which the innovations are deployed. Because the purpose of this model is to examine the effects of demand heterogeneity on technology development, and not the technological limits to development itself, the simplifying assumption of linear improvements is used.

⁹ In reality, the mapping between product and process innovation and changes in product performance and cost is not so clearly delineated as prior modeling suggests. The notion of design for manufacturing highlights the important role that product design may play in cost reduction. However, for the sake of simplicity, we maintain the stylized treatment of prior modeling efforts.

In every period, firms can choose to pursue a mix of product and process innovation or to forego innovative activity. The current state of the product is determined by the entire history of development activity and is therefore path dependent. Innovative outcomes are cumulative and therefore product cost and functionality cannot be manipulated instantaneously.

In the model, firms choose innovative activity on the basis of local search (March and Simon 1958, Nelson and Winter 1982). Firms are assumed to be able to predict consumer reaction to each incremental change to the product (i.e., development outcomes that will ensue within a single product or process innovation). However, firms do not make evaluations of potential consumer demand further away from their current product offering.

We explore behavior that corresponds to a symmetric Nash Equilibrium of a series of one-period games among two firms. Firms choose innovative activity and price so as to maximize their own payoff, assuming that their competitors' behavior remains constant. Thus, firms are modeled as making profit-maximizing choices, but based only on next period's payoff. Finally, we make the simplifying assumption that firms' initial product offerings are the same.¹⁰

The model is analyzed under two different product pricing regimes. The first pricing regime, "market pricing," posits that firms are fully informed regarding consumers' responses to pricing decisions and that the firms can, given their product's performance and production cost, determine the price point that will yield them the greatest profit. The second pricing regime, "heuristic pricing," assumes that firms price at a fixed markup over costs. This simplified pricing structure, while clearly nonoptimizing, is the most common form of pricing rule employed by businesses (Monroe 1990, 143).

The model results, discussed below, are remarkable for their robustness, given that these two pricing regimes represent polar cases of firm pricing decisions. While the choice of pricing regime affects the

absolute values of the simulation results, the pattern of product and process innovation behaviors that is the focus of this analysis is the same for both settings.¹¹ To economize on the exposition of the results, we present figures from the heuristic pricing case.

5. Analysis

The model is analyzed using a computer simulation programmed in Pascal. The first procedures of the simulation initialize both the population of consumers and initial characteristics of the product technologies. The population of consumers is composed of one hundred individuals, with each individual characterized by a minimum functionality requirement and a minimum utility level. The values of individual consumers' F_{i0} are uniformly distributed from 1 to 20 and P_{i0} values range from 1 to 7. The range of consumers' minimum functional thresholds is such that approximately twenty product innovation attempts are necessary to span the distance between the minimum requirements of the least and most demanding customer in the market.

Product technologies are introduced to the market at different points of functional development. We characterize two different settings of product entry. One is a "new to the world" technology. This is the typical setting examined in technology life cycle studies in which the initial product technology is functionally crude. With this initial setting, we observe the conventional technology life cycle in which product development is initially emphasized with a later shift in emphasis towards process innovation.

The other setting is a "new to the market" technology. Product technologies can be introduced in forms that are, relative to market demands, functionally advanced. This situation is characteristic of product

¹⁰ In the current modeling effort, we are trying to understand the effect of consumer heterogeneity on the pattern of product and process innovation for a single technological trajectory. A separate question is how different technological trajectories may compete with one another. (See Adner 2001.)

¹¹ Because the market-pricing regime allows for behavior that is more sensitive to immediate market opportunities (i.e., the particular preferences among consumers considering purchasing the product), the price patterns display greater sensitivity to the particular realization of consumer preferences in a given simulation run than those observed under the heuristic pricing. The relative pattern of product and process innovation, however, is the same for both cases.

technologies that are being modified for application in a new task setting, after having been previously introduced to other application domains. In this setting, the initial emphasis is on process innovations in order to lower the costs of the product sufficiently to penetrate larger segments of the latent market.

"New to the world" technologies are introduced at an initial performance level of 2 and an initial cost of 4. "New to the market" technologies are introduced at an initial cost of 10 and an initial performance of 15. For all the runs shown, $\alpha = 0.2$, $C^{\text{prod}} = 0.2$, $F^{\text{prod}} = 1$, $\Delta_c = 0.05$, and the heuristic markup is 20%. The firms' choice set for allocating development effort between product and process innovation is defined by the following four alternatives: pure product; 75% product, 25% process; 50% product and process; 25% product, 75% process; and pure process. In addition, firms may choose not to engage in any innovative efforts. Thus, we do not force firms to make a discrete choice of product or process innovation; rather, firms can make a more fine-tuned trade-off between enhancing the product features and shifting the product cost. Nevertheless, this structure precludes product innovations, such as design for manufacturing, that result in both lower production costs and higher product functionality.

After this initialization, the following sequence of events is repeated for one hundred periods. First, each firm surveys the demand environment to determine its profit expectation for each possible action (no innovation or one of the five development efforts). Second, the firms commit to the activity that will yield the highest expected profit. Third, individual consumers independently evaluate the available product offerings and decide whether any product satisfies their minimum functionality and utility requirements and, if so, what product provides them the maximum utility level. Finally, market outcomes are tallied and firms experience their actual market payoffs.

To test for stochastic robustness, the simulation was run 50 times with different randomly drawn populations. While the duration of each of the distinct phases of technology evolution varied with each specific population draw, the relative rates of innovation followed a similar pattern. To test for parametric robustness, simulation results were examined for a

variety of ranges for F_{i0} and P_{i0} for the consumer population and for different values of α between 0 and 0.5. While changing these parameter settings affected absolute values, the qualitative results were consistently observed.

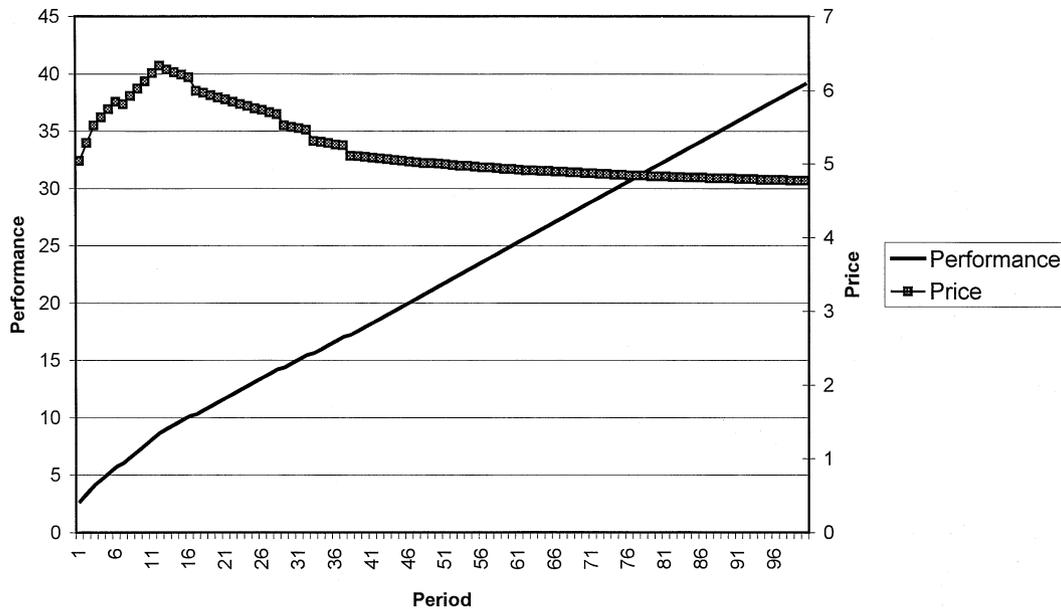
The absolute and relative attractiveness of product and process innovation is determined by the relationship among F^{prod} , C^{prod} , and Δ_c . These variables affect the qualitative results in a straightforward manner (increasing F^{prod} or decreasing C^{prod} makes product innovation more attractive, while increasing Δ_c makes process innovation relatively more attractive). Changing the ranges of F_{i0} and P_{i0} affects the populations' modal functionality and price requirements and shifts the absolute price and performance levels accordingly; again, such manipulations affect absolute values observed in any period, but not their relationship across periods, which is the focus of our analysis. The value of the parameter α affects the price trends observed in the mature demand phase, as discussed below. The parameters that have the greatest impact on the qualitative pattern of behavior, and which are the focal variables of the model analysis presented below, are the initial cost and performance attributes of the product.

6. Results

Three canonical phases of development activity can be identified during the course of the simulation according to their relative rates of product and process innovation. In the first phase, which we term *attribute equalization*, development actions are focused on achieving a balance between price and performance relative to the demands of the market. In this phase, one of the two innovation types is the dominant development mode. In the second phase, termed *market expansion*, development activities serve to expand market penetration through reductions in price, and thus process innovations are dominant. Finally, in the third phase of *demand maturity*, innovation activity is a balance of product and process innovation so that price remains relatively stable as product functionality increases.

The phases are identified by observing inflection points in product pricing behavior. The boundary

Figure 4 New to the World Technology with Competition (Markup 20%, Initial Cost 4, Initial Performance 2)



between the first and second stages is defined as the point of greatest negative change in the price slope. The boundary between the second stage and third stage is defined as the point of greatest positive change in the price slope. A representative simulation run for “new to the world” introductions is shown in Figure 4. The figures graph the levels of functional performance and price over time. The pattern of product and process innovation is most readily observed by following changes in product price, since in the case of heuristic pricing, product price is coupled to production cost and thereby directly reflects firms’ innovation choices. Price increases signal a focus on product development, while price decreases signal a focus on process development.

The first phase is characterized by an increase in product price, reflecting a focus on product development. The second phase, in which price decreases, reflecting the dominance of process development, begins at period 12 and ends at period 33. It is followed by the third phase that is characterized by relative price stability and steady performance improvements.

Figure 5 depicts the dynamics of technology development for products that are introduced to the market

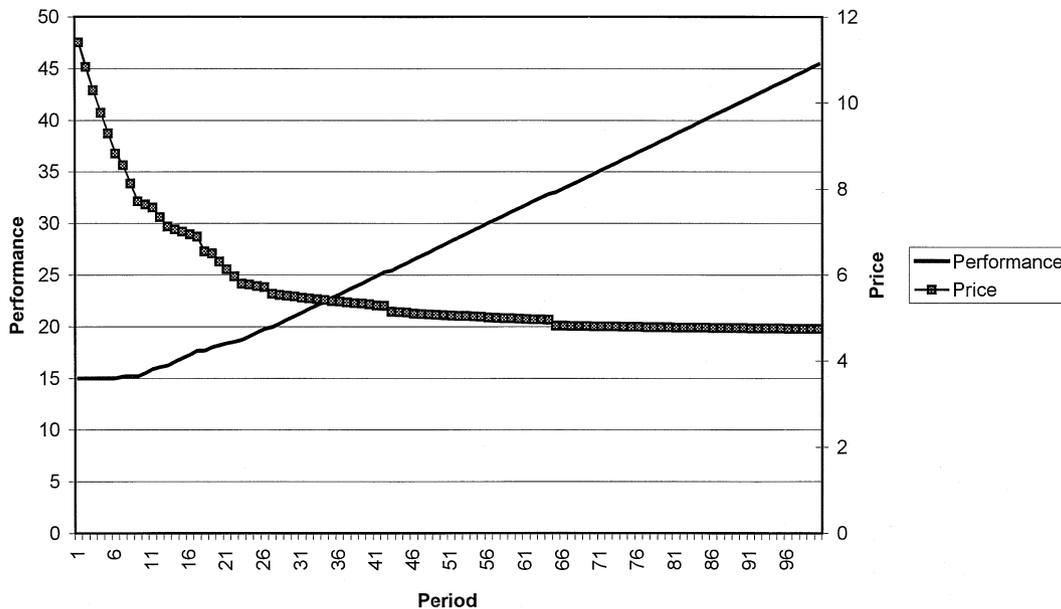
at a relatively advanced state of product development. In this case, the attribute equalization stage focuses on price reduction that not only balances the relative value of price and performance to meet market preferences, but at the same time also results in increased market penetration. As a result, the stages of attribute equalization and market penetration are effectively collapsed onto one stage. The third phase, demand maturity, begins in period 23 and has the same characteristics depicted for the case of “new to the world” product technology.

Examples of such “new to the market” technologies are the commercialization of space technology, or the “consumerization” of industrial goods. The development of home video cassette recorders, which built on a related product technology developed for industrial applications (Cusumano and Rosenbloom 1987), falls into this category; indeed, the price-performance history presented for VCRs in Figure 2 is similar to these simulations results.

Attribute Equalization

Recall that for a consumer to purchase a product, the product must satisfy or exceed the consumer’s threshold functionality and the product’s price must

Figure 5 New to Market Technology with Competition (Markup 20%, Initial Cost 10, Initial Performance 15)



be such that the net utility will satisfy or exceed the consumer's threshold utility level. At the early stage of market penetration, the innovation effort that will yield the greatest increase in sales and profit is the one that will meet the threshold requirements of the greatest number of current nonbuyers. This factor, whether functionality or price, is the focus of the initial innovative efforts.

Clearly, the product's initial cost and performance will determine the dimension on which initial innovative efforts are directed. In the traditional technology life cycle, this initial phase is dominated by product development activity. In "the new to the world" case, the model predicts an early focus on product development when the market penetration of the initial embodiment of a product is limited by its performance. Consider, for example, the market for early personal computers. The initial penetration of PCs was limited largely by the low functionality of the early PCs, rather than a prohibitive price. Early automobiles also suffered from an initial performance crisis: a car that breaks down every fifteen miles is no substitute for a horse, regardless of price.

In contrast, for product technologies that are introduced to the market at a functionality level that

is high compared to their affordability, price is the primary barrier to market penetration and, as a result, process development is the primary focus of early development efforts. Commercial applications of space technologies provide a clear example of such products. For example, the critical task for the commercialization of the Global Positioning System was not to improve the precision of the transmitter, but rather to lower the cost of the system from the thousands of dollars paid by government agencies to the \$500 price range at which commercial introduction was feasible (Pearce 1994).

The attribute equalization phase of innovative activity ends when the relative values of market price and product functionality correspond to consumers' preferences regarding the tradeoff between price and functionality. Development efforts face a tension between attracting new customers through engaging in product development and losing satisfied customers who are unwilling to pay the higher price charged for an improved product. In the conventional setting in which early innovative efforts focus on product innovation, this loss of established consumers due to price increases associated with product development is initially offset by the addition of

new consumers with higher quality thresholds who provide greater revenue per product purchase. After a certain point, however, efforts at market penetration via product enhancements become relatively less attractive as price considerations eclipse performance in governing market growth.

Market Penetration

The next phase of innovative activity is dominated by process developments which serve to "fill in" the market via price reductions. As product performance increases through the early product innovation efforts, firms face an increase in the latent set of consumers whose functionality requirements are satisfied by their product, but who are unwilling to purchase the product at its current price. This growing set of potential users, combines with the set of former buyers who have exited the market due to price considerations, induces firms to shift their development focus towards process innovation, lowering price and expanding their active market. Product price is reduced until the sales increases due to lower price no longer offset the revenue lost per product.

Demand Maturity

Eventually firms' development efforts yield a product whose functionality is such that the market as a whole is "satiated" with the existing quality of product offerings. The prospect of further incremental performance improvements will not significantly affect buying behavior with regards to either willingness to pay or the number of active buyers. However, individual firms still perceive opportunities for market share gains to be had by offering consumers better products. Because each firm evaluates its development options with regards to its rival's existing rather than potential product, each firm believes that market share gains will ensue if it offers a better product than was previously available to consumers. As a result, despite the reduction in willingness to pay for improvement on the part of consumers, firms, driven by competitive pressures, engage in significant levels of product innovation.

Consider the market's response to these efforts at performance improvement at the point at which con-

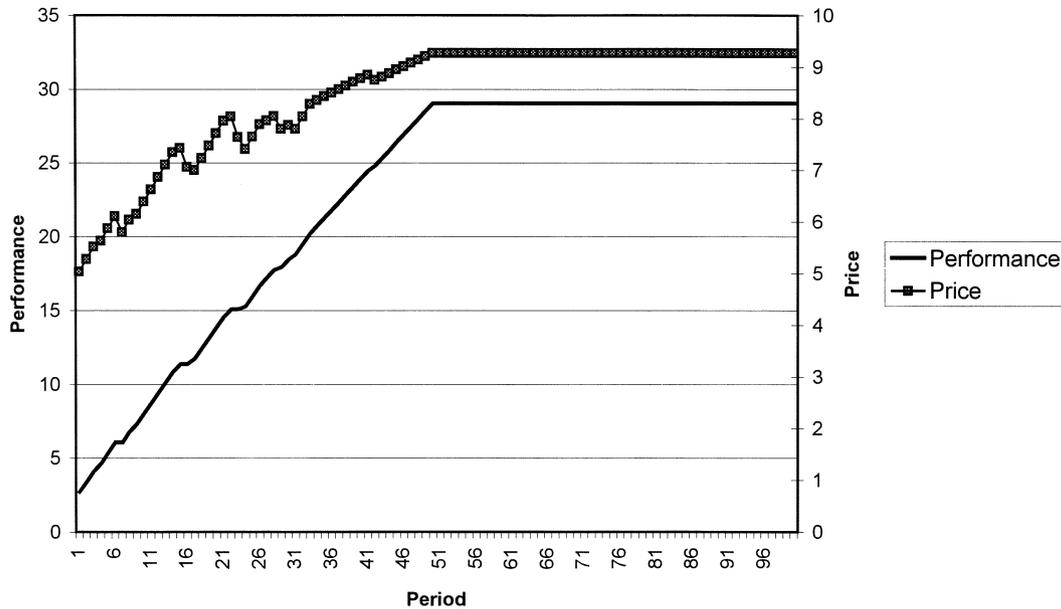
sumer willingness to pay for performance improvement has diminished. If the firm chooses to focus on product innovation, its production cost will increase. As it attempts to pass these increases onto the market, consumers at the low end will begin to drop out. As the market shrinks, the gains from higher product prices become insufficient to offset the loss of buyers and process innovation becomes the more attractive alternative. If the firm chooses to focus on process innovation and thereby reduces its production costs, competitive pressures will force the firm to pass some of these savings on to consumers. Successive process innovations lead to reductions in both the cost and price of the product, eventually leading to pressure on profit levels and, in turn, increasing the attractiveness of product innovation.

When consumer willingness to pay for performance improvements becomes relatively low, innovating firms face a tension between the loss of revenue due to decreases in unit volume associated with the higher prices that result from product development efforts and the loss of revenue due to the price decreases associated with process development. In the model, firms manage this tension by choosing to balance product and process innovation, keeping product price in a critical range that corresponds to the way that the aggregate market trades off the value of product performance and price.

This tradeoff is determined by the value of the parameter α in consumers' utility function, which specifies consumers' willingness to pay for performance improvements; that is, the degree to which performance improvements are subject to decreasing marginal utility. The lower the value of α , the lower is consumers' willingness to pay for performance improvements and the lower are both the product's price and the rate of increase in product price at maturity; conversely, higher values of α imply greater willingness to pay for improvements.

Thus, in the demand-maturity stage, product development becomes a way of maintaining product price rather than satisfying the needs of new customers. As a result of competition in the face of mature demand, product price remains relatively stable while product functionality experiences a steady rate of improvement.

Figure 6 New to World Technology with No Competition (Markup 20%, Initial Cost 4, Initial Performance 2)



The competitive dynamics underlying the demand maturity stage can be further illustrated by considering the development pattern observed for the case of a monopolist firm. Figure 6 illustrates representative results under a monopolist regime for a “new to the world” product introduction. Because the monopolist firm is not forced to offer consumers a more attractive product than its rival, it need only offer a product that satisfies consumers’ minimum requirements. As such, the demand landscape that the monopolist faces is a rather different one than that faced by a competitive firm. The monopolist is freer to initially exploit the willingness to pay higher prices for higher performance among higher end consumers. When demand matures, the monopolist, in the absence of competitive pressures to capture and defend market share, ceases to innovate entirely, and the sustained improvement observed under the competitive regime is absent. Indeed, for the case shown in Figure 6, all innovative activity ends in period 50. When innovation ceases to expand the market and consumers’ willingness to pay for improvements declines, the monopolist ceases innovation activity and consumers are faced with a static product. This qualitative pattern holds for both pricing regimes.

Firms in competitive situations seek to differentiate themselves from rivals in order to gain market advantage (Porter 1980). This need for differentiation continues as a function of rivalry, independent of the state of consumer satisfaction. The question still remains as to why producers do not offer lower-priced products at the functionality level at which consumer willingness to pay is largely exhausted, rather than improving functionality beyond this point.

Price reductions are attractive only to the extent that they attract new customers. After a certain point, the returns to market expansion via greater price reduction are outweighed by the foregone revenues from existing customers. As the product price falls below consumers’ willingness to pay, the consumers’ purchasing behavior is not changed. There is simply an increase in consumer surplus. Certainly price competition is a powerful driver of firm behavior, but to the extent that other avenues for attracting and retaining customers are available to firms, price competition will be attenuated.

The issue of satisfied demand raises the related question of why consumers would purchase advanced products that are clearly beyond their needs rather than holding out for more primitive prod-

ucts with lower prices. Ultimately, what the market dynamics generate is consumer surplus in the form of "luxurious bargains." As long as the magnitude of the incremental quality improvements that derive from product development offsets any associated price change, there will be a net increase in consumer surplus and the luxury of increased functionality will indeed be a bargain.

7. Discussion

The model developed here explores the interaction of innovation choices and consumer demand during the course of a technology's development. It shows that consideration of demand offers an alternative to supply side explanations of the technology life cycle. Early in a technology's development, innovation is guided by a drive to meet market requirements. In the later stages of development, after the market's price and performance requirements are met, innovation is driven by competition among suppliers faced with "technologically satisfied" consumers.

Under conventional ("new to the world") initial conditions, the demand-based model generates behaviors that are highly consistent with those documented in technology life cycle studies (e.g., Utterback and Abernathy 1978, DeBresson and Lampel 1985). Both approaches predict a product development focus and low market volumes in the early phases of development, with a process development focus in an intermediate stage accompanied by high market growth, and slower market growth in the final stage. While these patterns have been generally explained in terms of production technologies and producer entry (see Klepper 1997 for a review), the logic which drives the present results has a very different basis and is rooted in the underlying heterogeneity of the market environment.

While price trends similar to those predicted by the model for later stages of development are suggested by production experience curves (Boston Consulting Group 1972), experience curve explanations do not substitute for the demand-based framework presented here, but rather complement it. The present argument differs from experience curves in that it is concerned with an evolving product technology,

whereas experience curve arguments focus on the perfection of manufacturing techniques for a generally static product. As a result, experience curve arguments do not speak to the relative intensity of product and process innovation.

The demand-based model developed here also offers insight into the development patterns of products introduced under less conventional conditions, which do not follow the traditional technology life cycle. Furthermore, while previous models (Utterback and Abernathy 1975, Abernathy 1978, Gort and Klepper 1982) of the product life cycle predict decreased innovation activity in later stages of the life cycle, the model developed here suggests the possibility of high levels of innovative activity for mature product classes, consistent with a number of empirical findings (Henderson 1995, Christensen 1992, Klepper 1997). By introducing demand-based factors, the current model sheds new light on this observed, but previously unexplained, behavior in the product life cycle.

Model Boundaries

While the current modeling effort adds a degree of richness by incorporating demand considerations more explicitly into the analysis than prior efforts, it also inevitably imposes a number of simplifying assumptions.

One important assumption is that consumers' minimum functional requirements are assumed to remain constant over time. An increasing functionality requirement would necessitate the purchase of increasingly advanced products. Changes in minimum thresholds can result from changing expectations or from changing objective requirements. The quintessential example of evolving minimum thresholds is found in the context of personal computers. The minimum requirements of computers are continually ratcheted up as new software programs become more demanding of the technical requirements of the machines. The introduction of a new standard platform such as Windows 95, which provides consumers with the motivation to demand more powerful hardware, demonstrates how the presence of complementary goods can act to raise threshold requirements.

Alternatively, thresholds can be raised as expectations about product performance change—for example, the convenience of a palm-sized video camera has become a *de facto* home consumer requirement, which has effectively made obsolete the relevance of the ten-pound, shoulder-borne models of the early 1990s. To the extent that firms can actively affect consumers' minimum requirements, they can effectively rejuvenate their market position, postponing the difficult competitive environment brought on by mature demand.

Functionality thresholds may also change as the result of network externalities (Arthur 1989, David 1985). To the extent that such externalities are present, they would allow consumers to derive greater utility from a given product, as the user base (the number of consumers already purchasing the product) increases. This lowering of consumers' functional requirements would, in turn, allow firms to satisfy consumers' requirements earlier and with less development effort, but should not affect the qualitative dynamics of the innovative process.

The sudden appearance of sub-\$1,000 personal computers in 1997 presents a different sort of complication (Ramstad 1997): the emergence of a new application domain, the Internet, which (1) posed a lower performance requirement than existing thresholds; and (2) introduced a large number of new price-sensitive consumers into the market (purchasers of second computers and first-time, lower-income buyers). In addition, as the lower-end products produced to serve this segment have themselves been improved in response to this maturing demand, lower-end computers have begun to substitute for higher-end products. This displacement dynamic, however, lies outside the focus of the present paper.¹²

The model also does not explore the effects of product line strategies on firms' development decisions. While outside the scope of the current model, we can leverage our understanding of the current baseline dynamics to shed some light on the expected dynamics of product lines. For a "new to the world" product,

the key point of differentiation between the single product setting and that of a multiproduct product line occurs when early consumers threaten to stop purchasing the product because its price is rising due to improvements that they do not particularly value. In the multiproduct setting, we would expect firms to establish a low-end product to avoid losing current customers, while continuing to develop products targeted at more demanding users. At this point, a firm might offer a "basic" product to maintain its existing customer base and a higher end "advanced" product, which it would actively improve to capture new customers. The market would thus be segmented according to functionality and price. However, competitive pressure would force firms to improve their product in all market segments to maintain their share within each segment as characterized by the demand maturity.

In the limit, we could see the elimination of the market penetration phase. Rather, product trajectories could consist of an initial focus on product performance and then a shift, at different time periods and different levels of performance for each member of the product line, to the demand maturity pattern. In this case, the latent set of customers who had prompted the "fill in" dynamic of the market penetration phase would enter the market with the improving performance of sufficiently low-priced products rather than through the decreasing price of products with sufficient functionality, as in the single-product setting.

The central assumption underlying the result of "luxurious bargains" is that the potential for technological progress remains unexhausted even after the population's willingness to pay for improvement is largely exhausted. While the potential of technology performance relative to demand requirements can only be assessed on a case-specific basis, the rising dominance of electronic, computer, and information technology that has heralded the dawn of the "information age" suggests that the prevalence of such settings may be increasing (Kelly 1997). While oversatisfied demand for performance is by no means unique to the electronic context, electronic product

¹² The interested reader is referred to Christensen (1997) for an empirical examination of such technology disruptions and to Adner's (2001) analysis of technology competition in the context of heterogeneous market demand.

technologies have demonstrated a seemingly inexhaustible potential for improvement, both on the product performance side, with increases in speed, compactness, and reliability, as well as on the production process side, with tremendous reductions in the cost of obtaining these levels of performance. As such, they provide an ideal setting to study the dynamics of technology development when exogenous limits to development are not a primary constraint.

Viewing the evolution of technology through a demand-based lens suggests that the early evolution of technologies is guided by responding to the unsatisfied needs of the market. After sufficient development, however, firms face the intriguing possibility that these guiding needs have largely been satisfied. The framework developed here suggests that product maturity may be as much a function of satiated needs as it is of exhausted technologies. Mature consumer demand for performance in the face of unexhausted development trajectories places firms in the difficult position of needing to differentiate their offerings from those of their rivals, but of doing so for a consumer pool whose appreciation of performance improvements will not be reflected in their willingness to pay for the improved product. The competitive dynamics illustrated for the monopoly case, in which the monopolist ceases innovation at the point of demand maturity, illustrates the challenge posed by competition in the face of mature demand.

Highlighting the role of demand heterogeneity adds to our understanding of the role of selection forces on the evolution of product technology. While the exploration of path dependence has motivated a significant volume of work on technology evolution, the role of the demand context in which firms operate has received less attention. This bias in the literature has undermined our appreciation of the complexity of the demand environment and its potential for enriching our understanding of technology evolution.

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