

Consumer Preferences and Product and Process R&D*

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Abstract

I consider product and process R&D from the perspective of consumer preferences. In doing so, I find a novel distinction between the two. I find that the value of a process innovation depends only on quantity sold while that of a product innovation depends also on how much buyers are willing to pay for it and hence also on who buys the product. Over time, increased market penetration leads to a product being sold increasingly to people with a lower willingness to pay for quality improvements and hence relatively more of process R&D - a pattern observed in several industries. I also consider issues regarding social optimality of the division between product and process R&D chosen by firms, explain why US firms do relatively more of product R&D than Japanese firms as observed and several intra-industry observations about firm size and R&D.

JEL classification: O33, O32, L20

Keywords: Product R&D, process R&D, consumer preferences, willingness to pay for quality improvements

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1 Introduction

“It will be consumers who decide whether these solutions (wireless applications being developed using the wireless technology Bluetooth) are good ones or not.” - Paul Saffo, Director of Institute For The Future, speaking about Bluetooth in CNNdotCom on Sep 2nd, 2000.

Firms continually try to improve the quality of existing products and to create new products - *product R&D* - and also to lower the cost of making existing products - *process R&D*. For example, automatic data synchronization, better handwriting recognition and more screen space with a more readable screen are some recent product innovations in the hand-held computer industry. In contrast, better production techniques leading to lower reject rates would be an example of a process innovation. Consumer preferences often play an important and in many cases a (if not the) key role in determining these R&D choices.

While the management and the marketing literature are replete with articles highlighting the importance of understanding consumer needs in order to come up with better products and services,¹ economists have paid surprisingly little attention to this issue. Studies of R&D activities by firms in the economics literature have focussed mainly on the interrelationship of R&D and variables like firm size, market concentration, mode of competition and market structure² and have more or less ignored the interrelationship between R&D and consumer preferences.³ In this paper, I consider the interrelationship between firms' R&D choices

¹The importance of this issue has also been recognized in the economics literature, see for example, Chapter 10 in Rosenberg(1982) and also Cohen and Levin(1989).

²For example, see the surveys by Cohen and Levin(1989), and Symeonidis(1996).

³Some exceptions do exist. For example Sutton(1996, 1998) consider the choices made by firms between undertaking two different kinds of product R&D, namely improving the quality of existing products versus

and consumer preferences in a dynamic set-up with opportunities for firms to continually undertake both product and process R&D simultaneously.⁴

I begin by asking if there is any difference between product and process R&D that arises due to consumer preferences. This is a subtle conceptual question that to the best of my knowledge has not been answered satisfactorily till date - see for example, Cohen and Levin(1989). The standard notion of product R&D as R&D that shifts the demand curve outwards and process R&D as R&D that lowers production cost has the weakness that under such a broad definition, the two might have the same effect - see for example, Kline(2000). I use a discrete-choice model of consumer demand with vertical product differentiation. I find that a reduction in per-unit production cost by say a dollar means that a dollar is saved on every unit that is produced irrespective of who buys the product. However, the increase in revenue due to a product innovation depends not only on quantity sold but also on how much the buyers of the product are willing to pay for the innovation. Hence, *ceteris paribus* the value of a process innovation depends only on quantity sold while that of a product innovation depends on quantity sold and also on who buys the product - i.e. the degree of *market penetration* (defined as the fraction of potential buyers of a product who actually buy the product). Thus I find a hitherto unnoticed economic distinction between product and process R&D based on their relationship with consumer preferences.

Next, I consider whether this distinction can explain observations regarding firms' choices of product and process R&D. It is increasingly being recognized that these choices can have important ramifications - see for example Cohen and Klepper(1996a); hereafter **CK**. However, before any policy initiatives are undertaken in this regard, a clear understanding

developing new products and highlight the importance of variety in consumer tastes and needs in shaping these decisions. Another exception is Klepper(1996) which I discuss later.

⁴For a computer simulation model of a demand-based view of technology evolution, see Adner and Levinthal(2001) - hereafter AL.

of what drives firms' product and process R&D choices is needed. One pattern that has been identified is that firms typically do relatively more of process R&D over time. In fact, according to Klepper(1996), this is a defining characteristic of industry evolution in industries with opportunities for both product and process R&D. Over the years, a substantial body of mainly anecdotal evidence to this effect has been found in different industries - see references cited in Klepper(1996). More recently, Filson(2001b) estimates product and process R&D spending in the early automobile, personal computer, rigid disk drive, computer monitor and computer printer industries and also finds such a shift in R&D effort over time.

I consider a monopolistic industry in a multi-period set-up and solve the dynamic optimization problem of the firm. Potential buyers of the product differ in their willingness to pay for improvements in product quality. Further, the willingness to pay for the product and to pay for quality improvements are positively correlated - i.e. people with a higher willingness to pay for the product (consumers at the *higher end* of the market) also value quality improvements more than people with a lower willingness to pay for the product (consumers at the *lower end* of the market). However, the distribution of preferences across potential buyers of the product is invariant over time. The monopolist does both product and process R&D in each time period. This is in accord with Pine et al.(1993) who point out that while high quality and low cost were previously thought to be trade-offs, increasingly firms are in general continually trying both to improve product quality and lower production cost. Also, Landau and Rosenberg(1992) find that the most successful firms in the chemical processing industry in the 1980's were those that did both product and process R&D.

Due to continual product as well as process R&D, product quality improves and production cost decreases over time. The resultant increased market penetration leads to the product being increasingly sold to buyers at the lower end of the market. Thus, although the distribution of preferences across potential buyers of the product is time-invariant, the

willingness of the average actual buyer to pay for quality improvements is lower over time. Hence, the monopolist increasingly devotes more of its R&D effort to making the product cheaper.⁵ Put simply, in my model there is relatively more of process R&D over time because consumers want it to be so.

In the real world, consumer preferences indeed often play a major role in shaping R&D choices of firms. For example, the data storage powerhouse EMC conducts “customer councils” twice a year in North America and Europe and annually elsewhere in the world. These involve twenty hours of intense discussions over two and a half days between EMC executives and customers where EMC product management and engineering executives try to methodically extract product requirements from customers, check whether the concepts they are considering for future products meet customer needs and to find out what customers currently want and are likely to want in the future.⁶ Further, this is not an isolated example. Several companies such as Hewlett-Packard, Nissan, Toyota and Xerox to name a few, as part of their information-gathering process about customer needs for their R&D program even use a set of techniques called “*empathic design*” - see Leonard and Rayport(1997) - where they watch consumers use products or services to understand consumer needs that consumers themselves may not even recognize or be unable to articulate.

Further, consumer preferences can strongly influence the evolution over time of *R&D composition* - division of R&D effort between product and process R&D - chosen by firms as well. Consider for illustration hand-held computers which are used as electronic organizers and have recently become popular with the Palm Pilot. Initial users have been mainly (though not limited to) mobile professionals like doctors and corporate executives and gadget

⁵I also consider an industry with a dominant firm and a competitive fringe where only the dominant firm does R&D. Even then, R&D shifts towards relatively more of process R&D over time.

⁶Interview with the CEO of EMC, Harvard Business Review, January 2001, pp. 130-136.

freaks. Successive updated versions of the Palm Pilot and of competing products have in general tried to introduce more features than previous versions. The current emphasis in this industry thus seems to be more on making the product better than making it cheaper. Conceivably, some time in the future hand-held computers will be used by virtually everyone, even first-graders will have them in their backpacks. Presumably, the focus will by then shift more towards making the device cheaper rather than adding even more features to it.

Also, the change over time in the composition of the actual buyers of a product with respect to their willingness to pay for quality improvements which plays an important role in my model seems evident in many industries even from a casual observation. Typically, early buyers of a product care mainly about the features or the quality of the product and are willing to pay a lot for improvements in quality. In contrast, over time a product is usually sold increasingly to consumers at the lower end of the market who often find the product features sufficient for their needs and care more about price reductions than quality improvements. This has happened for PCs - see Filson(2001a) - and for computers in general - see Flamm(1988). Also, Tabrizi and Walleigh(1997) discuss the importance for firms of identifying the pioneers and risk-takers among the customers and engaging them in a dialogue regarding product needs since they are most likely to push existing products to their performance limits. Similarly, EMC carefully chooses the customers at its customer councils - see the interview with the CEO of EMC cited earlier - and focuses on the customers who are early adaptors since once the product satisfies their needs, it typically satisfies the needs of most other users to a large extent as well. Thus, this paper also reveals a link between the shift in R&D composition for a product and the change in composition of actual buyers of the product with respect to their willingness to pay for quality improvements over time.

Klepper(1996) and the dominant design hypothesis - hereafter **DDH** - provide alternative explanations for the shift towards relatively more of process R&D over time. Klepper(1996)

considers a perfectly competitive industry with no strategic interaction between firms either in the product market or regarding R&D. It assumes that product innovations can be sold or licensed in a disembodied form. Hence it assumes that the return to product R&D is independent of the output of the innovating firm and an exogenously given constant in all time periods. On the other hand, it assumes that process innovations cannot be sold or licensed at all. Hence the return to process R&D comes only through the output of the innovating firm. Thus it highlights advantages of firm size for R&D and provides a nice explanation of why large firms do more process R&D. Over time, firms in Klepper(1996) produce more and hence also do relatively more of process R&D.

While firms do license product innovations as in Klepper(1996), it is evident that innovating firms also benefit from product innovations through sales of their own products embodying their product innovations.⁷ In my framework, there are scale effects in returns to both process and product R&D. While the presence of scale effects in returns to process R&D and the lack thereof for product R&D is the driving force in Klepper(1996) in explaining the change in R&D composition over time, the difference in how returns to product and process R&D are related to consumer preferences and a decrease in the willingness of the average actual buyer to pay for quality improvements over time are the key ingredients in my framework.

According to DDH - see for example, Mueller and Tilton(1969), Abernathy and Utterback(1975) - when a product is first introduced there is considerable uncertainty about user needs and preferences and the technological means and possibilities of satisfying them. Hence, process innovations can be meaningfully attempted only after problems regarding

⁷Also, even if licensing was the main source of income from product innovations, the earnings from such a license would presumably depend on consumer valuation of the product innovation. Hence, the effects highlighted in this paper can be expected to continue to hold even in such a case.

product design have been tackled. Over time, standards and a dominant design (product with standardized features and capabilities) emerge. Following this, improvements in product design try to keep standardized product features almost unchanged. Consequently there are less opportunities for product R&D. Also, firms are more willing to try to improve the production process (process R&D). Hence, there is relatively more of process R&D over time.

I find the explanations in both Klepper(1996) and DDH complementary to my explanation. However, my framework can account for several features of industry evolution that the framework in Klepper(1996) cannot. Also, in addition to several criticisms that DDH faces - see for example, Klepper(1996) and AL - DDH cannot explain the inter-industry differences in R&D composition of US and Japanese firms discussed below which my framework can explain. Thus, my explanation along with these two provides a more complete picture of the choice between product and process R&D over the life cycle of a product.

I also consider how R&D composition chosen by a welfare-maximizing monopolist would evolve over time and how its choice differs from that by a profit-maximizing monopolist. While the answers to these questions can potentially have important policy implications - for a discussion see CK - little has been done in this regard. I find that even with a welfare-maximizing monopolist, since over time the product will be consumed by consumers with a lower willingness to pay for quality improvements, there will be relatively more of process R&D over time. Considering the case where a profit-maximizing and a welfare-maximizing monopolist produce the same exogenously given sequence of output,⁸ since a profit-maximizing monopolist can appropriate the entire gains from a process but not from a product innovation, it does the socially optimal amount of process but less than the socially optimal amount of product R&D and hence in terms of R&D composition, relatively more of process R&D than is socially optimal. Further, gains from product R&D that the profit-

⁸This assumption abstracts away the difference in output produced by the two that would otherwise arise.

maximizing monopolist cannot appropriate (increase in consumer surplus) increases and hence it undertakes a lower fraction of the socially optimal amount of product R&D over time. In this sense, there is *increasing inoptimality* over time. A *general subsidy to R&D* - subsidy given irrespective of whether expenditure is on product or process R&D - increases the amount of both product and process R&D by the profit-maximizing monopolist (leading to more process R&D than socially optimal) but leaves its R&D composition unchanged. Thus my results suggest that more focused measures like R&D subsidy targeted specifically towards product R&D and taking into account the increasing inoptimality over time would be needed to tackle the problem.

Further, I develop cross-sectional implications of my model. I begin by considering how R&D composition of two firms of the same size in two industries that differ in certain underlying economic factors might differ. Mansfield(1988) considers the R&D composition of Japanese and US firms belonging to the same industry and of approximately the same size and finds that US firms devote a much larger share of their R&D effort to product R&D than Japanese firms. It is natural to ask what differences in economic factors between the two countries might lead to such a difference. While the importance of this question has been recognized - see for example Mansfield(1988), CK, Athey and Schmutzler(1995); hereafter **AS** - to the best of my knowledge, this is the first paper that addresses this issue. I find that the firm engaging in a more myopic behavior does relatively more of product R&D. This is because a more myopic firm discounts future profits more and hence also the fact that over time, process innovations become relatively more valuable than product innovations since a product is increasingly sold to buyers with a lower willingness to pay for quality improvements. Both anecdotal and empirical evidence have been found that US firms generally attach more importance to short-term results than Japanese firms - see Jacobson

and Aaker(1993), Ito(1992) and references therein.⁹ Thus I find an economic explanation for the observed difference in R&D composition of US and Japanese firms. I am also able to explain several intra-industry empirical observations about firm size and R&D.

Finally, since consumer heterogeneity in willingness to pay for quality improvements throughout plays a crucial role in my model, it is natural to ask what happens if all potential buyers have the same willingness to pay for quality improvements. I find that in such a case, product and process R&D become equivalent and R&D composition is invariant over time.

The rest of the paper is organized as follows. Section 2 lays out the basic framework. Section 3 considers the difference between product and process R&D. Section 4 considers the evolution of R&D composition over time and issues related to the question of social optimality of R&D composition chosen by firms. Section 5 develops cross-sectional implications of my framework. Section 6 concludes. All proofs are in the appendix.

2 The Model

2.1 Preferences, Production and R&D

Basic set-up: I consider the industry for a non-durable product. The product is character-

⁹Managers of a firm typically know more about its true state of earnings and long-term prospects than outside investors. This can lead to myopic behavior on their part - for a theoretical model, see Stein(1989). In the US, there is a well-developed and funded equity market and limited ties between investors or banks and firms. In Japan however, close ties between the two often exist due to the widely-prevalent cross-ownership of stock and the existence of “financial keiretsu” (horizontally integrated enterprise groups). Hence there is typically more asymmetric information between investors and managers in the US compared to Japan resulting in US firms being generally more myopic than Japanese firms. Further, this is not restricted to a US-Japan comparison only. Financial markets in the UK resemble those in the US and empirical evidence of a similar difference between British and Japanese firms has been found - see Becchetti(1995).

ized by a single one-dimensional product attribute - quality - denoted by $s, s \in \mathfrak{R}_+$. Time is discrete. There are n time periods - $t = 0, \dots, n-1$; n any positive but finite integer. Period 0 denotes the first time period in which the product is commercially introduced in the market. The mass of potential buyers of the product in each time period - denoted M_t in period t - is exogenously given. The only restriction on M_t is that $\forall t \in \{0, \dots, n-1\}, M_t \in (0, \hat{M})$; \hat{M} a positive, finite number. Thus M_t can vary over time. After period $n-1$, the mass of potential buyers of the product is 0 - i.e. the product becomes obsolete. Thus, I consider a product with an arbitrary but finite lifespan.¹⁰ There is a numeraire good. Price of the product, utility that a consumer gets from buying the product and R&D expenditure, costs, revenues and profits are measured in terms of this numeraire good.

Preferences: I use the discrete-choice model of consumer demand with vertical product differentiation as in Mussa and Rosen(1978) and Maskin and Riley(1984). This is a well-accepted model of consumer preferences with vertically differentiated products and has the empirically observed feature that higher quality products enjoy higher mark-ups.

Formally I assume that each potential buyer buys either 0 or 1 unit of the product in each period. There are two real-valued preference parameters θ and v , both non-negative and finite with $(\theta, v) \in [\theta_1, \theta_2] \times [v_1, v_2]$. A consumer with preference parameters (θ, v) gets a utility of $\theta s + v - P$ from buying one unit of the product of quality s at price P and buys one unit

¹⁰Note that by lifespan, I mean the time following the development of a commercially viable product. The development of a prototype is usually quite costly. This is often followed by a period of time where the main effort is to reduce production costs since the product may not be commercially viable unless sold below a certain price. Thus if one considers R&D composition right from the development of a product, one might observe initially an almost exclusive focus on product R&D, followed by an almost exclusive focus on process R&D and then both product and process R&D as the product is sold and feedback becomes available from the users. Since the evidence regarding the choice between product and process R&D corresponds to the time after the development of a commercially viable product, this is the time-frame that I analyze.

of the product provided this utility is non-negative. Thus θ reflects a consumer's willingness to pay for quality improvements. The distribution of (θ, v) across potential buyers - denoted by F - is exogenously given and invariant over time. Thus while M_t can vary over time, the distribution of (θ, v) across the potential buyers is always the same. I assume that F admits a pdf f which is positive $\forall (\theta, v) \in [\theta_1, \theta_2] \times [v_1, v_2]$. I also assume that a consumer's choice of buying or not buying the product in any time period has no effect on the consumer's choice set or utility in subsequent time periods.

I consider two cases. One - hereafter **Case D** - where θ varies across consumers while v is the same for everyone¹¹ (here I normalize the value of v to be 0). This represents a scenario where consumers differ in their willingness to pay for quality improvements. Note that in this case, as in Mussa and Rosen(1978) and Maskin and Riley(1984) consumers with a higher total willingness to pay for the product are also the ones with a higher willingness to pay for quality improvements - this is one of the keys to my results. The other - hereafter **Case S** - where θ is the same for everyone while v varies across consumers representing a scenario where all consumers have the same willingness to pay for quality improvements. Also, hereafter $F()$ will therefore unless otherwise stated denote the distribution of θ in Case D and that of v in Case S.

Industry structure: I consider a monopolistic industry with a single firm which produces the product. The monopolist knows the lifespan of the product, has a discount parameter $\beta \in [0, 1]$ and maximizes its discounted profit over the lifespan of the product. The monopolist is characterized by two parameters - s and c . s denotes the quality of the product produced by the monopolist. All consumers and the monopolist agree on the value of s - i.e. there is complete information about product quality. c is the cost characteristic of the monopolist.

¹¹Note that all my results for Case D hold even if v also varies across consumers provided between any two consumers, the one with a higher θ also has (at least a weakly) higher v .

The monopolist has a production function with zero fixed costs and a constant marginal cost of production c which is independent of s . I call (s,c) , the characteristic vector of the monopolist. The initial characteristic vector - denoted (s_0, c_0) - is exogenously given. I assume parameter values to be such that the cost characteristic of the monopolist is non-negative over the lifespan of the product.

R&D: The monopolist can do both product and process R&D - that is try to increase the value of s ¹² and lower the value of c respectively - in each period. The returns to R&D are deterministic. Formally, let (s_t, c_t) denote the characteristic vector of the monopolist at the beginning of period t while r_t^Q and r_t^C denote product and process R&D expenditure respectively in period t . Then at the end of period t , the monopolist ends up with $s_{t+1} = s_t + a_t^Q g(r_t^Q)$ and $c_{t+1} = c_t - \mu_t a_t^Q g(r_t^C)$ ¹³ where $g()$ is of the form: $g(r) = r^\lambda$. Here a_t^Q and $\mu_t a_t^Q$ are the productivity for product and process R&D respectively in period t - a higher value for either means that the same amount of R&D spending yields a greater quality improvement or cost reduction respectively - and can vary over time. Note that μ_t is an index of the *technological merit* of doing process relative to that of doing product R&D - this can as in the technology evolution literature also be interpreted as the opportunity for process relative to that for product R&D. I assume that $\lambda \in (0,1)$,¹⁴ $\forall t \in \{0, \dots, n-1\}$,

¹²Product quality often has multiple dimensions and consumers may differ in their needs along these different dimensions. Also, firms often try to - at times simultaneously - improve product quality in several different directions, an example being the introduction of several new varieties. One way of interpreting my assumption of one-dimensional quality and product R&D as trying to improve this one-dimensional variable is to think of s as a composite index for quality and product R&D as improving this composite index. Alternatively, it can be thought of as the firm trying to identify and improve the commonalities in the product features that most consumers value - "*value innovations*", see Kim and Mauborgne(1997).

¹³This functional form of returns to R&D has been used elsewhere in the literature - for example Klepper(1996). It is also analogous to the form of returns to R&D assumed in Sutton(1998).

¹⁴Note that λ is the elasticity of R&D output - amount of increase in s or decrease in c - with respect to

$a_t^Q \in (0, \hat{a})$ and $\mu_t \in (0, \hat{\mu})$; \hat{a} and $\hat{\mu}$ finite, positive numbers and that both product and process innovations are cumulative.

Sequence of events: Events unfold as follows. At the beginning of a period, the monopolist first decides how much to spend on product and process R&D during that period. I assume that the monopolist has no financial constraints in this regard. Then the outcome of R&D is realized after which production takes place. Thus in period t , the monopolist sells a product of quality s_{t+1} which it produces at a per-unit cost of c_{t+1} . The monopolist cannot price discriminate between various consumers, has no capacity constraints and faces no potential threat of entry.

A comment: AS consider a two-period model where a monopolist decides on organizational structure in the first and product and process R&D in the second period and consider how these are interrelated. Each period in my framework is like the second period in AS except that I explicitly model how returns to product and process R&D arise from the monopolist's decisions coupled with consumer preferences instead of taking them to be exogenously given as in AS. Thus my framework is analogous to a multi-period version of AS taking the organizational structure of the firm to be exogenously given.

2.2 Preliminary results

In any time period, the monopolist takes two decisions - how much to spend on product and process R&D and how much of the product to sell in that period. I use the following notation.

Notation: N.i) $x_t \in [0, 1]$ is the fraction of potential buyers to whom the monopolist sells - and thus *the degree of market penetration* by the monopolist - in period t .

N.ii) $p(x, s)$ is the resultant price - inverse demand for the product - with degree of market R&D expenditure. The assumption that $\lambda \in (0, 1)$ is consistent with the findings of Acs and Audretsch(1988).

penetration x , product quality s and $M = 1$.¹⁵

x is a choice variable for the monopolist. For convenience of exposition, throughout this paper while discussing profit-maximization, I will consider the profit-maximizing choice of the degree of market penetration - this is equivalent to considering the profit-maximizing choice of output.

N.iii) $p_2(x, s) \equiv \frac{\partial p(x, s)}{\partial s}$ - note that since f is positive $\forall (\theta, v) \in [\theta_1, \theta_2] \times [v_1, v_2]$, $p(x, s)$ is continuous and differentiable.

N.iv) $MR(x, s) \equiv \frac{\partial [p(x, s)x]}{\partial x}$ is the marginal revenue curve of the monopolist with respect to x when degree of market penetration is x , product quality is s and $M = 1$.

N.v) $V(t, s, c)$ denotes the value function of the monopolist when it starts off with the characteristic vector (s, c) and the product has a lifespan of t periods.

I make the following assumptions.

Assumptions: A1: $\frac{d^2}{dx^2}[xF^{-1}(1-x)] < 0 \forall x$.¹⁶

A2: $\theta s_0 + v > c_0$ for some $(\theta, v) \in [\theta_1, \theta_2] \times [v_1, v_2]$.

Decision regarding quantity: Since the product is non-durable, the monopolist's quantity choice in a given period does not affect future sales. So, to decide how much to sell in period t , the monopolist solves

$$\max_{x \in [0, 1]} [p(x, s_{t+1}) - c_{t+1}] x M_t \quad (1)$$

Notation: N.vi) $x(s, c) \equiv \operatorname{argmax}_{x \in [0, 1]} [p(x, s) - c] x M$ - thus $x(s, c)$ is the profit-maximizing choice of x for the monopolist when it has a characteristic vector (s, c) .

Given my assumptions regarding consumer preferences, it follows that $p(x, s) = [F^{-1}(1-x)]s$ in case D while $p(x, s) = \theta s + F^{-1}(1-x)$ in case S. Thus an increase in s shifts the

¹⁵If the mass of potential buyers is M , then $P(Q, s) = p(\frac{Q}{M}, s)$ is the inverse demand for the product where $Q \in [0, M]$ denotes total quantity demanded.

¹⁶This is true for example if for any $x \in [0, 1]$, in Case D, $F(\theta_1 + (\theta_2 - \theta_1)x) = x^\alpha$ while in Case S, $F(v_1 + (v_2 - v_1)x) = x^\alpha$ where $\alpha \geq 1$ ($\alpha = 1$ corresponds to the uniform distribution in either case).

demand curve outwards in either case. However, while the demand curve shifts outward in a parallel fashion in case S, in case D lower the value of x , greater the upward shift in the demand curve following an increase in s . Thus, in case D an increase in s shifts the demand curve outwards and also makes it steeper. Also, from the expression for $p(x, s)$, it follows that $MR(x, s) = \frac{d}{dx}[xF^{-1}(1-x)]s$ in case D while it is equal to $\theta s + \frac{d}{dx}[xF^{-1}(1-x)]$ in case S. Hence, A1 implies that $MR(x, s)$ is strictly decreasing in x guaranteeing a unique solution to (1). Further, it follows that

Fact: F1: i) In case D, if $MR(x, s)$ is positive, it is strictly increasing in s .

ii) In case S, $MR(x, s)$ is always strictly increasing in s .

Decision regarding R&D: Consider period t . Let $\pi(s_t, c_t, r_t^Q, r_t^C)$ denote the monopolist's profit in that period taking into account the R&D expenditure incurred during the period.

Then

$$\pi(s_t, c_t, r_t^Q, r_t^C) = [p(x_t, s_t + a_t^Q g(r_t^Q)) - (c_t - \mu_t a_t^Q g(r_t^C))]x_t M_t - r_t^Q - r_t^C \quad (2)$$

where $x_t = x(s_t + a_t^Q g(r_t^Q), c_t - \mu_t a_t^Q g(r_t^C))$.

Since product and process innovations are cumulative, the monopolist's choice of product and process R&D in any period affects its profit in that as well as in subsequent periods.

Hence, the monopolist's dynamic optimization problem - $V(n, s_0, c_0)$ - is given by

$$V(n, s_0, c_0) = \max_{\{r_t^Q, r_t^C\}_{t=0}^{n-1}} \sum_{t=0}^{n-1} \beta^t \pi(s_t, c_t, r_t^Q, r_t^C) \quad (3)$$

where $s_{t+1} = s_t + a_t^Q g(r_t^Q)$ and $c_{t+1} = c_t - \mu_t a_t^Q g(r_t^C) \forall t \in \{0, \dots, n-1\}$.

Dynamics of quality, cost and market penetration: I find that

Lemma 1: s_{t+1} increases while c_{t+1} decreases with t ; $t \in \{0, \dots, n-1\}$.

Lemma 2: \exists finite numbers say s_{max} and c_{min} such that $s_{n+1} \leq s_{max}$ and $c_{n+1} \geq c_{min}$.

Both process and product R&D in any time period lead to an increase in the degree of market penetration and hence an increase in the quantity sold by the monopolist in that

period. This in turn leads to a greater incentive for the monopolist to do both product and process R&D. Thus as in AS, product and process R&D are complementary. Lemma 2 implies that the monopolist's dynamic optimization problem is well-defined. I make one more assumption.

Assumption: A3: Even if $s = s_{max}$ and $c = c_{min}$, the market is not covered - i.e. $x_t < 1 \forall t \in \{0, \dots, n-1\}$.

Lemma 3: x_t increases with t .

3 Difference between product and process R&D

From the monopolist's dynamic optimization problem [equation (3)], using the envelope theorem it follows that $\forall t \in \{0, \dots, n-1\}$, the optimal product and process R&D expenditure satisfy the following FONC's:

$$\text{FONC for } r_t^C [\text{process R\&D}]: \left[\sum_{k=t}^{n-1} \beta^{k-t} x_k M_k \right] \mu_t a_t^Q g'(r_t^C) = 1 \quad (4)$$

$$\text{FONC for } r_t^Q [\text{product R\&D}]: \left[\sum_{k=t}^{n-1} \beta^{k-t} p_2(x_k, s_{k+1}) x_k M_k \right] a_t^Q g'(r_t^Q) = 1 \quad (5)$$

where in both (4) and (5), $x_t = x(s_{t+1}, c_{t+1})$.

Consider (4) and start by assuming that $\beta = 0$ - i.e. the monopolist is myopic. In period t , if r^C has been spent on process R&D, spending 1 more unit on process R&D lowers c further by $\mu_t a_t^Q g'(r^C)$. Ignoring the consequent change in the profit-maximizing output, the benefit to the monopolist from the lower cost is the resultant amount saved in the cost of producing the output sold which equals the reduction in production cost times output sold. At the margin, by the envelope theorem only the "direct effect" matters and hence r_t^C must satisfy $x_t M_t \mu_t a_t^Q g'(r_t^C) = 1$. With $\beta \neq 0$, since innovations are cumulative, the benefit from lowering c in period t also includes the resultant benefit obtained in subsequent periods

leading to (4).

On the other hand, consider (5). Again start by assuming that $\beta = 0$. In period t , if r^Q has been spent on product R&D, spending 1 more unit on product R&D improves s further by $a_t^Q g'(r^Q)$. Ignoring the consequent change in the profit-maximizing output, the benefit to the monopolist from the improved quality is the resultant extra revenue that the monopolist can earn. This equals the amount by which the monopolist can raise the price (which equals what the marginal buyer is willing to pay for a unit improvement in product quality - $p_2(x_t, s_{t+1})$ - times the increment in quality) times output sold. The same argument as before leads to (5). Comparing the two FONC's it follows that

Proposition 1: (Difference between product and process R&D) *For a given sequence of the amount of output to be sold by the monopolist over time, in any time period*

(i) *returns from process R&D depend only on the sequence of outputs and the process R&D productivity*

while

(ii) *returns from product R&D depend on the sequence of outputs and the product R&D productivity as well as on the composition of buyers of the product with respect to their willingness to pay for quality improvements.*

Corollary 1, Proposition 1: *In case S, from an economic perspective product and process R&D are equivalent.*^{17,18}

Different ideas have been put forth regarding the distinction between product and process R&D. One is the technological idea underlying DDH discussed earlier; another - see

¹⁷In this case, in any period t , the FONC for product R&D is simply the FONC for process R&D scaled by the factor $\frac{\theta}{\mu_t}$ for all values of the degree of market penetration - i.e. the degree of market penetration has no effect on the relative choices of process and product R&D.

¹⁸Kline(2000) has shown in a similar set-up that a product innovation and a process innovation can have the same effect. Corollary 1, Proposition 1 generalizes this finding.

Klepper(1996), Cohen and Klepper(1996a) - is that process innovations are exploited more heavily through an innovating firm's own output than product innovations. According to another view - see Eswaran and Gallini(1996), Rosenkranz(1996) - the two differ in that process R&D by lowering production cost intensifies competition while product R&D lessens the competition faced by a product by differentiating it from other similar products.

Proposition 1 shows another way in which the two differ. Most discussions regarding product and process R&D - including AS, Klepper(1996), CK and DDH- simply consider product R&D as R&D that shifts the demand curve outwards and process R&D as R&D that lowers the production cost and ignore details regarding how the demand curve shifts following product R&D. As discussed earlier, graphically at any point on the demand curve, the amount of the outward shift in demand due to a unit increase in quality depends on the willingness of the corresponding buyer to pay for quality improvements leading to the demand curve also becoming steeper in Case D while a unit reduction in c always lowers the cost curve in the same fashion. Mathematically, the price-cost margin per-unit of output depends on $\theta_m s - c$; θ_m being the value of θ for the marginal buyer. Hence the value of a unit increase in s per unit of output depends on θ_m while that of a unit decrease in c is always the same. Thus the two are different. However if everyone has the same willingness to pay for quality improvements, the two become equivalent.

4 R&D composition

In this section, I consider how the choice between product and process R&D is affected by the distinction between the two found in Section 3.

4.1 Evolution of R&D composition

I begin by considering how the choice between product and process R&D evolves over time.

I use the following notation.

Notation: N.vii) S_t^{proc} denotes the share of process R&D in the monopolist's total R&D expenditure in period t - thus, $S_t^{proc} = \frac{r_t^C}{r_t^C + r_t^Q}$.

To abstract away from any effects of a change in the technological merit of process relative to product R&D over time so as to focus exclusively on the effects of consumer preferences, I make the following assumption.

Assumption: Throughout this section unless otherwise stated, μ_t is a constant - denoted μ - over time.

I find that

Proposition 2: (Evolution of R&D composition over time)

(i) **Case D:** (Heterogeneity in willingness to pay for quality improvements) *In case D, S_t^{proc} is an increasing function of time.*

(ii) **Case S:** (Homogeneity in willingness to pay for quality improvements) *In case S, S_t^{proc} is a constant over time.*

Intuition behind Proposition 2: The key to Proposition 2(i) is the fact that in case D, the willingness of the marginal buyer to pay for quality improvements is lower over time. There are two factors behind this. One is the positive correlation between the willingness to pay for quality improvements and the total willingness to pay for the product. The other is the increase in market penetration by the monopolist over time.

Both product and process innovations are cumulative. Hence, s improves and c decreases [Lemma 1] and since $MR(x, s)$ is increasing in s , market penetration is also higher [Lemma 3] over time. In case D, consumers with a higher total willingness to pay for the product are also the consumers with a higher value of θ . Hence greater market penetration means selling

to people with a lower value of θ . Consequently the willingness of the marginal buyer to pay for quality improvements is lower over time. Since the incentive for process R&D depends on the level of output and R&D productivity only while that for product R&D depends both on the level of output and R&D productivity and the marginal buyer's willingness to pay for quality improvements [Proposition 1], we get Proposition 2(i). In case S, since all consumers have the same value of θ , the willingness of the marginal buyer to pay for quality improvements and hence S_t^{proc} is invariant over time [Proposition 2(ii)]. Further note that in case S, R&D composition is invariant over time regardless of how market penetration by the monopolist evolves over time. In fact, Proposition 2(ii) can be obtained without any of the assumptions made regarding $F()$ and $MR(,)$.

Note that the specific functional form assumed for R&D technology is not critical in obtaining Proposition 2. In the proof of Proposition 2, $g'(r_t^C)/g'(r_t^Q)$ - "return from one more unit of process relative to that from one more unit of product R&D" - decreases over time in case D while it is a constant in case S. This follows simply from how the willingness of the marginal buyer to pay for quality improvements changes over time. Hence, diminishing marginal returns to R&D suggests that S_t^{proc} increases over time in case D but is a constant in case S. The specific functional form assumed for $g()$ is simply a sufficient condition to guarantee an inverse relationship between $g'(r_t^C)/g'(r_t^Q)$ and r_t^C/r_t^Q .

Incorporating other real-life observations: In Klepper(1996), over time (a) the rate of quality improvement diminishes - while this is partly due to entry and exit of firms, at an individual firm level, the rate of quality improvement is time-invariant (b) the rate of cost reduction increases (c) profitability of product innovation is constant (d) price falls and (e) technology for both product and process R&D are time-invariant. However, Filson(2001b) finds that (a) and (b) - specially (a) - need not be true. In fact, the rate of quality improvement can behave in a non-monotone fashion and can have a U-shape - see Filson(2001a and

b) and also AL. Filson(2001b) also finds that the profitability of quality improvements may vary and could be higher over time. It has also been observed that in the later stages of the life cycle of a product, there comes a phase that is characterized by increasing product quality but a more-or-less stable price - see AL, also Filson(2001b). Further, the technology for R&D often changes over the life cycle of a product - see for example Filson(2001a).

The benefit from product or process R&D depends on two factors: the *value factor* - benefit from a quality improvement or cost reduction discussed in Section 3 - and the *technological factor* - amount of quality improvement or cost reduction resulting from an R&D expenditure. Both my explanation and Klepper(1996) focus exclusively on the value factor. While Klepper(1996) focusses on the difference in the output over which the benefit from a quality increment or a cost reduction is realized, my explanation focusses on the difference in the benefit per unit of output from such improvements. Both uncover similar increases in the benefit from a cost reduction relative to that from a quality increment over time to explain the observed shift in R&D composition.

In Case D of my framework, in period t the rate of quality improvement, the rate of cost reduction, profit from a unit quality improvement and price are given by $\frac{a_t^Q g(r_t^Q)}{s_t}$, $\frac{\mu_t a_t^C g(r_t^C)}{c_t}$, $x_t M_t F^{-1}(1-x_t)$ and $[F_1^{-1}(1-x_t)]s_{t+1} + F_2^{-1}(1-x)$ respectively - where $(F_1^{-1}(1-x), F_2^{-1}(1-x)) = (\theta, v)$ for the consumer with the top x percentile value for willingness to pay for the product among all potential buyers.¹⁹ Both x_t and s_{t+1} increase over time. Further, other than time-invariance of μ_t , the only restriction on process and product R&D productivity and on $\{M_t\}_{t=0}^{t=n-1}$ is that each is always positive and has a finite, upper bound. Thus, for suitable choices of parameter values, my framework would be able to incorporate the real-life observations mentioned earlier while providing another, demand-based explanation

¹⁹Here, I am relaxing the simplifying assumption that v is same for everyone. This does not change any of my results - see discussion in Section 2.1. Also, the value of v enters only in the expression for price.

complementary to Klepper(1996) for the observed shift in R&D composition over time.

4.2 Alternative scenarios

In this subsection, I consider how the evolution of R&D composition over time is affected when some of the assumptions made in the original set-up are relaxed. In subsections 4.2.1-4.2.3 below, I find that in Case S, S_t^{proc} is a constant over time.

4.2.1 Price discrimination

Suppose the monopolist can perfectly price discriminate between the various potential buyers. Then

Corollary 1, Proposition 2: (Perfect price discrimination)

Case D: *If θ is distributed uniformly, S_t^{proc} increases over time.*

4.2.2 Financial constraints

Suppose the monopolist has an exogenously given R&D budget in each period t denoted as R_t . For simplicity, I assume that this sequence of R&D budgets is not related in any way to the performance of the monopolist. Then

Corollary 2, Proposition 2: (Limited R&D budget)

Case D: *S_t^{proc} increases over time.*

4.2.3 Uncertainty

Consider the following scenario. There are only 2 time periods; 0 and 1 - i.e. $n = 2$. At $t = 0$, there is uncertainty regarding returns to R&D in period 1. Two things can happen. Given any choice of (r_0^Q, r_0^C) , the monopolist might find it optimal at $t = 1$ to choose (a)

$(r_{1,1}^Q, r_{1,1}^C, x_{1,1})$ - **Scenario 1** (b) $(r_{1,2}^Q, r_{1,2}^C, x_{1,2})$ - **Scenario 2** where $x_{1,1} \neq x_{1,2}$;²⁰ also note that the R&D choices in the two scenarios will most likely be different. At $t = 0$, it is only known that in period 1, scenario 1 will occur with probability γ while scenario 2 will occur with probability $(1 - \gamma)$; $\gamma \in (0, 1)$. At the beginning of $t = 1$, the monopolist knows which scenario has occurred.

This uncertainty could be due to different reasons. It could arise on the demand side or on the R&D side - for example, an uncertainty regarding M_1 or a_1^Q . Note that the formulation here is similar to the modelling of uncertainty regarding returns to R&D in AS. I find that

Corollary 3, Proposition 2: (Effect of uncertainty) *Suppose $x_{1,1} > x_{1,2}$. Then Case D: a) if scenario 1 occurs, $S_1^{proc} > S_0^{proc}$.*

b) if scenario 2 occurs, $S_1^{proc} > (<)S_0^{proc}$ if $\gamma < (>)\frac{x_0[F^{-1}(1-x_0)-F^{-1}(1-x_{1,2})]}{\beta x_{1,2}[F^{-1}(1-x_{1,2})-F^{-1}(1-x_{1,1})]}$.

Corollary 3, Proposition 2(i) shows that with uncertainty, an adverse shock can possibly revert the increase in S_t^{proc} over time that would otherwise occur in case D. The intuition behind this result is as follows. If the monopolist expects to achieve high market penetration in the future, it does relatively more of process R&D in the current period based on that expectation. Also, stronger the expectation more the shift towards process R&D. When the “future arrives”, if high market penetration is achieved the monopolist ends up doing relatively more of process R&D over time by the argument underlying Proposition 2(i). However, if high market penetration is not achieved, it does relatively less of process R&D. Consequently, if the expectation of high market penetration had been “strong enough”, the monopolist might end up doing relatively more of product R&D in a later period compared to an earlier period.

²⁰The second subscript here stands for the scenario while the first subscript stands for the time period.

4.2.4 Quality-dependent cost

Suppose production cost is related to product quality. Note that improved quality could lead to either higher or lower production costs - see for example, a discussion in this regard in Filson(2001b). Let $I(s)$ denote the effect of product quality on the per-unit production cost where $\forall s, I(s) \geq 0$. I consider two possible scenarios. One - hereafter **Scenario 1** - with a per-unit cost of production given by $c + I(s)$ and a second - hereafter **Scenario 2** - where the per-unit cost of production is given by $cI(s)$. In either case, the value of c can be lowered by process R&D as before. Again as before, c decreases and s increases over time. In Scenario 1, in addition to the effects in my original framework, improvements in s due to the presence of $I(s)$ lower or increase the incentive for product R&D over time depending on whether $I'(s)$ is positive or negative. If this additional disincentive increases or the additional incentive decreases with s , then it provides an additional shift to R&D composition towards relatively more of process R&D over time. I find that

Corollary 4(a), Proposition 2: (Quality-dependent cost) *In scenario 1, (i) Case D:*

S_t^{proc} increases over time if $I''(s) \geq 0$.

(ii) Case S: S_t^{proc} is a constant, increases or decreases over time provided $I''(s) = 0$, $I''(s) > 0$ or $I''(s) < 0$ respectively.

Further, even if $I''(s) < 0$, in Case D it could still be that S_t^{proc} increases over time.

In scenario 2, since the amount by which a product innovation raises or lowers cost depends on the value of c , process R&D in addition to the usual complementary effect on product R&D also increases or lowers the incentive for product R&D over time by lowering c . Similarly, product R&D provides an increasing or decreasing additional incentive for process R&D over time by increasing s . The direction of evolution of S_t^{proc} in this case depends on the relative magnitudes of these two additional effects.²¹ With $I'(s) > 0 \forall s$, I find that

²¹For a more detailed discussion, in this regard as well as the case of quality-dependent mass of potential

Corollary 4(b), Proposition 2(i): (Quality-dependent cost) *In scenario 2, Case D: Suppose θ is uniformly distributed and $I(s) = \tau \ln(\frac{s}{s_0}) + C$; C a constant and $\tau \in (0, \frac{1}{2})$ - i.e. the increase in per-unit production cost due to an increase in s is “not too large”. Then S_t^{proc} increases over time.*

4.2.5 Quality-dependent mass of potential buyers

Suppose, M_t is not exogenously given but is a function of product quality - say $M_t(s_{t+1})$ - where $M'_t(s) > 0 \forall s$. Then, a product innovation in period t leads to an increase in M_k ; $k \in \{t, \dots, n-1\}$ and hence there is an additional incentive for product R&D - namely, the discounted sum of the price-cost margin in each subsequent period k times the increase in M_k . The evolution of S_t^{proc} depends on the magnitude of this additional effect. I find that

Corollary 5, Proposition 2(i): (Quality-dependent M_t) Case D: *Suppose θ is uniformly distributed and in any period t , $M_t(s_{t+1}) = m_t(s_{t+1})^\kappa$; $\{m_t\}_{t=0}^{t=n-1}$ and κ positive constants, $\kappa \in (0, 1)$ - i.e. increase in mass of potential buyers due to an increase in s is “not too large” - and \exists finite, upper bound for $\{m_t\}_{t=0}^{t=n-1}$. Then, S_t^{proc} increases over time.*

4.2.6 Incorporating DDH

Suppose, μ_t increases over time. This is consistent with the main premise of DDH - see corresponding discussion earlier. Then in this case,

Corollary 6, Proposition 2: (Incorporating DDH) *there is an additional effect which*

(i) **Case D:** *complements increase in S_t^{proc} over time due to $p_2(x_t, s_{t+1})$ decreasing over time.*

(ii) **Case S:** *leads to S_t^{proc} being increasing over time.*

buyers - discussed next - and some other alternative scenarios not discussed here, see Saha(1999).

4.2.7 Product market competition

Consider the case with a dominant firm and a competitive fringe competing in the product market. To keep things simple, I assume that only the dominant firm - the **R&D firm** - does R&D. Everything else is as in my original set-up. Also, each fringe firm has a time-invariant characteristic vector (s_f, c_f) where $s_f < s_0$. I will only consider case D since with case S, only the firm with the highest product quality will sell anything and the R&D firm will always devote the same fraction of its R&D effort to process R&D. I find that

Corollary 7, Proposition 2(i):(Dominant firm-competitive fringe set-up) *Suppose parameter values are such that either a) $c_{n+1} > c_f$ or b) $\frac{d}{dx}[xF^{-1}(1-x)]$ evaluated at $x = 1 - F(\frac{c_f}{s_f})$ is non-negative.²² Then S_t^{proc} increases over time.*

4.3 Social optimality

Here I address the following questions: (a) How will R&D composition if chosen by a welfare-maximizing social planner vary over time? (b) Are product and process R&D choices of the monopolist socially optimal (in the sense of maximizing welfare)? (c) How does the answer to (b) vary with time? and (d) If the answer to (b) is NO, then can a “general” subsidy to R&D rectify the problem?

In order to answer these questions, I consider how a profit-maximizing monopolist - hereafter **Firm P** - and a welfare-maximizing monopolist - hereafter **Firm W** - will behave. Let $r_{t,X}^Q$, $r_{t,X}^C$ and $S_{t,X}^{proc}$ denote product R&D, process R&D and the resultant S^{proc} chosen by firm X in period t ; $X \in \{P, W\}$. I find that

Proposition 3: (Social optimality of R&D composition)

²²If these assumptions do not hold, the R&D firm in the presence of the fringe might choose x^* such that $\frac{d}{dx}[xF^{-1}(1-x)]|_{x=x^*} < 0$. Then $MR(x, s)$ for the R&D firm is decreasing in s and it cannot be analytically determined how S_t^{proc} evolves over time.

(i) **Case D: (a)** Suppose θ is distributed uniformly. Then $S_{t,W}^{proc}$ increases over time.

For (b)-(d), suppose firms P and W produce an exogenously given, fixed sequence of output $\{Q_t\}_{t=0}^{t=n-1}$ and only decide how much of process and product R&D to do in each period to maximize the discounted sum of their respective objective functions over the n periods.²³

(b) $\forall t, r_{t,W}^Q > r_{t,P}^Q, r_{t,W}^C = r_{t,P}^C$ and $S_{t,P}^{proc} > S_{t,W}^{proc}$.

(c) Suppose $\{Q_t\}_{t=0}^{t=n-1}$ is such that $x_t > x_{t-1}; t \in \{1, \dots, n\}$ ²⁴ and θ is uniformly distributed. Then $\frac{r_{t,P}^Q}{r_{t,W}^Q}$ decreases over time.

(d) Suppose for each unit spent on R&D irrespective of whether it is spent on process or product R&D, firm P gets δ from the government; $\delta \in (0,1)$ - a “general R&D subsidy”. This does not change $S_{t,P}^{proc}$ for any t .

(ii) **Case S:** $\forall t, r_{t,P}^Q = r_{t,W}^Q, r_{t,P}^C = r_{t,W}^C$; also, $S_{t,P}^{proc}$ (and also $S_{t,W}^{proc}$) does not vary over time.

In case D, firm P captures the entire benefit from any process R&D but not the entire benefit from product R&D (part of it goes to the consumers). Hence, we get (b). $r_{t,P}^Q/r_{t,W}^Q$ depends inversely on the ratio of increase in consumer surplus to gain to firm P in period t and subsequent periods from a unit increment in s . Hence, with any distribution for which this ratio increases with an increase in the degree of market penetration (one example being the uniform distribution), (c) holds. A general subsidy to R&D increases the incentive for both product and process R&D by the same extent. Hence it increases the amount of both process and product R&D undertaken by firm P (note that in such a case, firm P does more process R&D than is socially optimal) in each period but leaves S_t^{proc} unchanged for any t . Firm W takes into account the increase in consumer surplus arising from product R&D.

²³In most scenarios including my framework, for the same parameter values a welfare-maximizing social planner produces more than a profit-maximizing monopolist. This difference in output will lead to a difference in their R&D choices. Assuming the same sequence of outputs for both allows for a more meaningful comparison between the two.

²⁴This is in accord with the dynamics of market penetration found earlier.

However, since over time the product is sold increasingly to people who benefit less from quality improvements, firm W also finds it optimal to do relatively more of process R&D over time. Also note that Proposition 3(i) (b)-(d) hold even if μ_t varies over time.

5 Cross-sectional results

Here, I develop cross-sectional implications of my framework. To do so, I consider the following extension of my original framework. Suppose an industry consists of K identical and independent submarkets (K a finite, positive integer) where there can be at most one firm in each submarket. Each submarket has the same structure as in my original framework. The submarkets are independent in the sense that what happens in one submarket - either in the product market or regarding R&D - has no effect on any other submarket. Firms enter the industry over time.²⁵ Each firm that enters operates in a separate submarket²⁶ and its actions have no effect on any other firm. So, there can be several firms within an industry. These firms can be of different sizes depending on when they entered the industry and their initial characteristic vector. This formulation is analogous to the **Independent Submarkets with Single Products** setting in Sutton(1998) and also to a market with segmentation or clustering according to a number of “principles of differentiation” - see Bresnahan et al.(1997) - with at most one firm in each segment or cluster. Further, throughout this section, I only

²⁵Let $N_t \equiv$ number of firms in the industry in period t . The entry process can be exogenous or endogenous. For an example of an endogenous entry process, suppose that in any given period, each potential entrant must incur a fixed cost to try to enter. The probability of success in entering of any such potential entrant depends on and is decreasing in both N_{t-1} and E_t - number of firms trying to enter in period t . Then E_t and N_t are endogenously determined. Further, in such a case E_t decreases over time which agrees with one of the defining characteristics - see Klepper(1996) - of the product life cycle model of industry evolution.

²⁶I am considering operations in different submarkets as different firms. With independent submarkets, allowing a single firm to operate in several submarkets does not change anything.

consider case D and unless otherwise specified **assume** that $\beta = 0$.

5.1 Inter-industry differences

Note that $\Gamma \equiv \{\theta_1, \theta_2, F(\theta), g(), n, (s_0, c_0), \{M_t\}_0^{n-1}, \{a_t^Q\}_0^{n-1}, \{\mu_t\}_0^{n-1}\}$ defines a submarket. Consider *two different industries* - **Industry 1** and **Industry 2**. In any given period t , consider a firm from industry 1 - **firm 1** - and a firm from industry 2 - **firm 2** - that are producing the same output - *firms of the same size*. Suppose that both industries have the structure as described above with possibly different values of K . Also while the value of $\{n, (s_0, c_0), \{a_t^Q\}_0^{n-1}\}$ can vary across submarkets both within each industry and across the two industries, any submarket in either industry has the same value for $\{\mu_t\}_0^{n-1}$ - $\{\mu_t\}_0^{n-1}$ need not be time-invariant - and the remaining components of Γ ²⁷ except that

Case (a): in any period t , the mass of potential buyers in any submarket in industry 1 is greater than that in any submarket in industry 2.²⁸

Case (b): for any $x \in [0, 1]$, $F^{-1}(1 - x)$ in any submarket in industry 1 is greater than $F^{-1}(1 - x)$ in any submarket in industry 2.

Case (c): for each firm in industry 1, $\beta = 0$ while for each firm in industry 2, $\beta > 0$ - further in this case, the time period being considered is not the last period in the lifespan of the product for firm 2.

Let $S_{t,i}^{proc}$ denote S_t^{proc} for firm i , $i \in \{1, 2\}$. Then

Proposition 4: (Inter-industry comparison of R&D composition) *In each of the three cases above, $S_{t,1}^{proc} < S_{t,2}^{proc}$.*

²⁷If industry 1 and industry 2 are the same industry but in two different countries, they might differ in R&D productivities, lifespan and the initial characteristic vector due to differences in country-specific factors. However being the same industry, it seems reasonable to expect them to have the same value for merit of doing process relative to product R&D. Thus the set-up here matches that used in Mansfield(1988).

²⁸Here, all submarkets in an industry may or may not have the same value of M_t .

Corollary 1, Proposition 4, Case (c): *With the set-up as in this subsection, Case (c) but with Case S of my framework and μ_t increasing over time [as in Section 4.2.6], $S_{t,1}^{proc} = S_{t,2}^{proc}$.*

Discussion of Proposition 4: Case (c) Proposition 4, Case (c) shows that my viewpoint regarding product and process R&D can also explain the observed difference in R&D composition between US and Japanese firms. Here, both firms have the same market penetration. Firm 1 is myopic and considers only the profit in the current period. Firm 2 is forward-looking and takes into account not only current profit but also the fact that it will achieve more market penetration in the future and in response to that ends up doing relatively more of process R&D than firm 1.

Ceteris paribus, the relationship between the amount of quality improvement or cost reduction and the corresponding R&D expenditure in any period affects product and process R&D choices in that period only and has no effects on these choices in any subsequent period. Hence, as shown by Corollary 1, Proposition 4, Case (c), DDH or any explanation of industry evolution that focusses solely on the change in the relative opportunity for product and process R&D over time will be unable to explain any inter-industry differences in R&D composition between firms of the same size and having the same R&D opportunities and market conditions. Thus while such technological forces are indeed operative and important, one must also consider the effects of changes in the value factor of benefit from product relative to that from process R&D over time.

Cases (a) and (b): In Case (a), since firm 1 is selling to a larger mass of potential buyers (larger market size), firm 1 and firm 2 being of the same size means firm 1 has achieved less market penetration than firm 2 and hence does relatively more of product R&D. In Case (b), both firms have achieved the same market penetration but buyers in market 1 have a higher willingness to pay for quality improvements than buyers in market 2 and hence firm 1

does relatively more of product R&D.²⁹ Examining the empirical validity of the predictions in Cases (a) and (b) is a potential area for further research.

5.2 Intra-industry patterns

There is a large literature on intra-industry cross-sectional regularities regarding R&D choices of firms. Here, I consider whether my framework can generate these regularities or not.

Consider an industry with a structure as described at the beginning of this section. Further, while the value of $\{n, (s_0, c_0)\}$ can vary across submarkets within this industry, all submarkets have the same value for $\{\mu_t\}_0^{n-1}$ - $\{\mu_t\}_0^{n-1}$ need not be time-invariant - and for the remaining components of Γ . Hence, Proposition 5 below holds even if submarkets within an industry vary in their lifespan or the initial characteristic vector. In any period t , consider *two different firms within this industry* - **firm 1** and **firm 2** - and assume that firm 1 produces more than firm 2 - i.e. firm 1 is larger than firm 2. Let $r_{t,i}^Q$, $r_{t,i}^C$ and $S_{t,i}^{proc}$ denote product R&D expenditure, process R&D expenditure and share of process R&D in total R&D expenditure for firm i in period t ; $i \in \{1, 2\}$. Then

Proposition 5: (Firm size and R&D choices)

$$\begin{aligned} \text{(a.i)} \quad & r_{t,1}^C > r_{t,2}^C \quad \text{(a.ii)} \quad r_{t,1}^Q > r_{t,2}^Q \quad \text{(a.iii)} \quad S_{t,1}^{proc} > S_{t,2}^{proc} \\ \text{(b.i)} \quad & \frac{\mu_t a_t^Q g(r_{t,1}^C)}{r_{t,1}^C} < \frac{\mu_t a_t^Q g(r_{t,2}^C)}{r_{t,2}^C} \quad \text{(b.ii)} \quad \frac{a_t^Q g(r_{t,1}^Q)}{r_{t,1}^Q} < \frac{a_t^Q g(r_{t,2}^Q)}{r_{t,2}^Q} \end{aligned}$$

Proposition 5(a) shows that in my framework, in absolute terms a larger firm does more of process as well as product R&D and thus more of R&D as a whole - numerous studies have found that in general larger firms do more R&D, for a review see Cohen and Klepper

²⁹The result in Case (b) holds for any two firms, one from industry 1 and one from industry 2 irrespective of their relative size, even if $\beta \neq 0$ and the range of values and the distribution of θ are neither time-invariant, nor necessarily the same in the two industries provided $\min_{t \in \{0, \dots, n-1\}} F_{(t,1)}^{-1}(0) > \max_{t \in \{0, \dots, n-1\}} F_{(t,2)}^{-1}(1)$; $F_{(t,i)}^{-1}(z) \equiv F^{-1}(z)$ in industry i in period t , $i \in \{1, 2\}$, $z \in [0, 1]$.

(1996b) - while in relative terms it does relatively more of process R&D than a smaller firm - for evidence to this effect, see CK and earlier work cited therein. $\frac{a^Q g(r)}{r}$ and $\frac{\mu a^Q g(r)}{r}$ are the ratios of R&D output to spending for product and process R&D respectively - i.e. the amount of innovation generated per dollar spent. Thus, Proposition 5(b) shows that in my framework, a larger firm has a lower R&D productivity for both process and product R&D than a smaller firm - such a relationship has been observed, see for example Acs and Audretsch(1988, 1991) and earlier work cited therein. It might seem curious as to why a firm with lower R&D productivity ends up doing more R&D. Note that this has nothing to do with R&D capabilities of firms - in fact here in any given time period, all firms are equally efficient at R&D. Since there are scale effects in returns to both product and process R&D in my framework, a larger firm benefits more from any process or product innovation and hence does more of both than a smaller firm. However due to diminishing returns to R&D, return per dollar of R&D spending is lower with more R&D and hence lower at a larger firm.

Incorporating another real-life observation: In Klepper(1996) and in fact, any explanation of industry evolution that ignores effects of quality differences across firms, a large firm size necessarily means a lower production cost. Note that my framework can incorporate this not necessarily being true - a feature observed in the real world, see Filson(2001a).

6 Comments and further research:

In this paper, I consider product and process R&D from the perspective of consumer preferences. In doing so, I find a novel distinction between the two. This distinction can explain the observed shift in R&D effort towards relatively more of process R&D over time. My explanation also links the shift over time in R&D composition to that in willingness of the average actual buyer to pay for quality improvements. I also consider issues related

to whether R&D composition chosen by firms is socially optimal or not, provide insights into why there might be inter-industry differences in R&D composition chosen by firms of the same size and explain several intra-industry observations regarding firm size and R&D choices of firms.

Developing the framework of this paper further to incorporate strategic interaction between firms both in the product market and R&D remains a topic for further research. Another interesting extension would be to embed the model used here in a framework with product ladders where a product does not suddenly become obsolete after some time. In such a case, new products would possibly attract buyers with high willingness to pay for quality improvements away from old products leading to cycles of R&D composition with a shift towards process R&D over time along each cycle.³⁰ It would also be interesting to try to sort the relative importance of the key factors in DDH, Klepper(1996) and this paper in shaping R&D composition - for some work in this direction, see Klepper and Simons(1997). Further, with more and more globalization, firms are increasingly entering new markets. This is possibly changing their R&D decisions in general and choice of R&D composition in particular. On the other hand, consumer preferences and their willingness to pay for quality improvements are also possibly changing as a result. Analyzing the interrelationship between these changes seems to be another promising area for further research.

7 Appendix

Proof of Lemma 1: From A2 it follows that $x_0 > 0$ even if both r_0^Q and r_0^C equal 0. However, since $\lim_{r \rightarrow 0} g'(r) = \infty$, both r_0^Q and r_0^C are positive. Since innovations are cumulative, by F1 x_t is non-decreasing over time. Hence by the same argument as above, the result follows. ■

³⁰The framework here describes one such cycle. For a further discussion in this regard, see Saha(1999).

Proof of Lemma 2: Consider (4) and (5). In (5), $p_2(x_k, s_{k+1})$ is the willingness to pay for quality improvements and hence the value of θ of the marginal buyer in period k . Since $\theta \in [\theta_1, \theta_2]$, M_t and a_t^Q have finite upper bounds and $g''() < 0$, \exists finite upper bounds for r_t^Q and r_t^C , $t \in \{0, \dots, n-1\}$. Hence from the fact that the industry has a finite lifespan, the result follows. ■

Proof of Lemma 3: Follows from Lemma 1, fact F1 and assumption A3. ■

Proof of Proposition 1: Follows from the discussion preceding it. ■

Proof of Proposition 2: From (4) and (5) we get

$$\frac{g'(r_t^C)}{g'(r_t^Q)} = \frac{\sum_{k=t}^{n-1} \beta^{k-t} p_2(x_k, s_{k+1}) x_k M_k}{\mu \sum_{k=t}^{n-1} \beta^{k-t} x_k M_k}; t \in \{0, \dots, n-1\} \quad (6)$$

Some algebraic manipulation yields: for $t \in \{0, \dots, n-2\}$

$$\begin{aligned} \frac{\sum_{k=t}^{n-1} \beta^{k-t} p_2(x_k, s_{k+1}) x_k M_k}{\sum_{k=t}^{n-1} \beta^{k-t} x_k M_k} &= \frac{\sum_{k=t+1}^{n-1} \beta^{k-t} p_2(x_k, s_{k+1}) x_k M_k}{\sum_{k=t+1}^{n-1} \beta^{k-t} x_k M_k} \\ &+ x_t M_t \frac{[\sum_{k=t+1}^{n-1} \beta^{k-t} (p_2(x_t, s_{t+1}) - p_2(x_k, s_{k+1})) x_k M_k]}{(\sum_{k=t}^{n-1} \beta^{k-t} x_k M_k)(\sum_{k=t+1}^{n-1} \beta^{k-t} x_k M_k)}; \end{aligned} \quad (7)$$

Thus,

$$\frac{g'(r_t^C)}{g'(r_t^Q)} = \frac{g'(r_{t+1}^C)}{g'(r_{t+1}^Q)} + x_t M_t \frac{[\sum_{k=t+1}^{n-1} \beta^{k-t} (p_2(x_t, s_{t+1}) - p_2(x_k, s_{k+1})) x_k M_k]}{\mu (\sum_{k=t}^{n-1} \beta^{k-t} x_k M_k)(\sum_{k=t+1}^{n-1} \beta^{k-t} x_k M_k)}; t \in \{0, \dots, n-2\} \quad (8)$$

Further,

$$\textbf{In Case D: } p(x_k, s_{k+1}) = F^{-1}(1 - x_k) s_{k+1}; \textbf{ hence } p_2(x_k, s_{k+1}) = F^{-1}(1 - x_k) \quad (9)$$

By Lemma 3, x_k is strictly increasing in k . Since F admits a pdf f and $f > 0 \forall x$, $F^{-1}(1 - x)$ is strictly decreasing in x . Thus in Case D, $p_2(x_k, s_{k+1})$ is strictly decreasing in k and hence, $g'(r_t^C)/g'(r_t^Q)$ decreases with time.

$$\textbf{In Case S: } p(x_k, s_{k+1}) = \theta s_{k+1} + F^{-1}(1 - x_k); \textbf{ hence } p_2(x_k, s_{k+1}) = \theta \quad (10)$$

Thus in case S, $g'(r_t^C)/g'(r_t^Q)$ is constant over time.

The functional form of $g()$ implies that

$$\frac{g'(r_t^C)}{g'(r_t^Q)} = \frac{1}{\left(\frac{r_t^C}{r_t^Q}\right)^{1-\lambda}}. \quad (11)$$

Since $0 < \lambda < 1$, (11) implies a 1-1 decreasing relationship between the value of $g'(r_t^C)/g'(r_t^Q)$ and r_t^C/r_t^Q . Hence, Proposition 2 follows. \blacksquare

Proof of Corollary 1, Proposition 2: Case D: In period t , the monopolist's profit from the product market is given by $\int_{\frac{c_{t+1}}{s_{t+1}}}^{\theta_2} [\theta s_{t+1} - c_{t+1}] M_t f(\theta) d\theta$. If θ is uniformly distributed over $[\theta_1, \theta_2]$, the value of the expression above can be explicitly computed. Using that, I find that in this case, the monopolist's R&D expenditure must satisfy:

$$\text{FONC for } r_t^C: \left[\sum_{k=t}^{n-1} \frac{\beta^{k-t} (\theta_2 - \frac{c_{k+1}}{s_{k+1}}) M_k}{(\theta_2 - \theta_1)} \right] \mu a_t^Q g'(r_t^C) = 1; t \in \{0, \dots, n-1\} \quad (12)$$

$$\text{FONC for } r_t^Q: \left[\sum_{k=t}^{n-1} \frac{\beta^{k-t} (\theta_2^2 - \frac{c_{k+1}^2}{s_{k+1}^2}) M_k}{2(\theta_2 - \theta_1)} \right] a_t^Q g'(r_t^Q) = 1; t \in \{0, \dots, n-1\} \quad (13)$$

Case S: In period t , the monopolist's profit from the product market is given by

$\int_{c_{t+1} - \theta s_{t+1}}^{v_2} [\theta s_{t+1} - c_{t+1} + v] M_t f(v) dv$. Here, the monopolist's R&D expenditure must satisfy:

$$\text{FONC for } r_t^C: \left[\sum_{k=t}^{n-1} \beta^{k-t} (1 - F(c_{k+1} - \theta s_{k+1})) M_k \right] \mu a_t^Q g'(r_t^C) = 1; t \in \{0, \dots, n-1\} \quad (14)$$

$$\text{FONC for } r_t^Q: \left[\sum_{k=t}^{n-1} \beta^{k-t} \theta \{1 - F(c_{k+1} - \theta s_{k+1})\} M_k \right] a_t^Q g'(r_t^Q) = 1; t \in \{0, \dots, n-1\} \quad (15)$$

Using (12)-(15), noting that c_t decreases while s_t increases as t increases and proceeding as in the proof of Proposition 2, the result follows. \blacksquare

Proof of Corollary 2, Proposition 2: In this case, the monopolist solves

$$\max_{[S_t^{proc}]_{t=0}^{n-1}} \sum_{t=0}^{n-1} \beta^t [p(x_t, s_{t+1}) - c_{t+1}] x_t M_t \quad (16)$$

where $s_{t+1} = s_0 + \sum_{k=0}^t a_k g([1 - S_k^{proc}] R_k)$, $c_{t+1} = c_0 - \sum_{k=0}^t a_k g(S_k^{proc} R_k)$ and $x_t = x(s_{t+1}, c_{t+1})$.

From (16), I find that for $t \in \{0, \dots, n-1\}$

$$\text{FONC for } S_t^{proc}: \frac{g'([1 - S_t^{proc}] R_t)}{g'(S_t^{proc} R_t)} = \frac{\mu \sum_{k=t}^{n-1} \beta^{k-t} x_k M_k}{\sum_{k=t}^{n-1} \beta^{k-t} p_2(x_k, s_{k+1}) x_k M_k} \quad (17)$$

Using (17), noting that x_t increases as t increases and proceeding as in the proof of Proposition 2, the result follows. \blacksquare

Proof of Corollary 3, Proposition 2: Here, in period 0 the monopolist solves

$$\max_{[r_0^Q, r_0^C]} [p(x_0, s_1) - c_1]x_0M_0 + \beta[\gamma\pi_{1,1}^{gross} + (1 - \gamma)\pi_{1,2}^{gross}] - r_0^Q - r_0^C \quad (18)$$

where $\pi_{1,i}^{gross} = (p(x_{1,i}, s_{2,i}) - c_{2,i})x_{1,i}M_{1,i}$ is the monopolist's profit in period 1, scenario i ignoring its R&D expenditure in period 1; also, $s_{2,i}$, $c_{2,i}$ and $M_{1,i}$ denote s at the end of, c at the end of and mass of potential buyers in period 1, scenario i , $i \in \{1, 2\}$ ($M_{1,1} = M_{1,2}$ if the uncertainty is not due to demand factors). Then the monopolist's R&D expenditure in period 0 satisfy the following FONC's[(19) for process R&D, (20) for product R&D]:

$$[x_0M_0 + \beta\gamma x_{1,1}M_{1,1} + \beta(1 - \gamma)x_{1,2}M_{1,2}]\mu a_0 g'(r_0^C) = 1 \quad (19)$$

$$[\{F^{-1}(1 - x_0)\}x_0M_0 + \beta\gamma\{F^{-1}(1 - x_{1,1})\}x_{1,1}M_{1,1} + \beta(1 - \gamma)\{F^{-1}(1 - x_{1,2})\}x_{1,2}M_{1,2}]a_0 g'(r_0^Q) = 1 \quad (20)$$

Let $r_{1,i}^C$ and $r_{1,i}^Q$ denote the monopolist's optimal process and product R&D expenditure respectively in period 1, scenario i , $i \in \{1, 2\}$. Then from (4) and (5), it follows that $\frac{g'(r_{1,i}^C)}{g'(r_{1,i}^Q)} = \frac{F^{-1}(1 - x_{1,i})}{\mu}$, $i \in \{1, 2\}$. Proceeding as in the proof of Proposition 2, I find that for any θ

$$\frac{g'(r_0^C)}{g'(r_0^Q)} - \theta = \frac{(B_0^{prod} - \theta)x_0M_0 + \beta[(\gamma)x_{1,1}M_{1,1}(B_{1,1}^{prod} - \theta) + (1 - \gamma)x_{1,2}M_{1,2}(B_{1,2}^{prod} - \theta)]}{\mu[x_0M_0 + \beta\{\gamma x_{1,1}M_{1,1} + (1 - \gamma)x_{1,2}M_{1,2}\}] \quad (21)$$

where $B_0^{prod} = F^{-1}(1 - x_0)$, $B_{1,i}^{prod} = F^{-1}(1 - x_{1,i})$, $i \in \{1, 2\}$. Since $x_{1,1} > x_{1,2}$, it follows that $F^{-1}(1 - x_{1,1}) < F^{-1}(1 - x_{1,2})$. By the argument underlying Proposition 2, both $x_{1,1} > x_0$ and $x_{1,2} > x_0$. Hence, using the expression for $\frac{g'(r_0^C)}{g'(r_0^Q)}$ in period 1 above and (21) and proceeding as in the proof of Proposition 2, the result follows. \blacksquare

Proof of Corollary 4(a), Proposition 2: In this case, the FONC for process R&D is still given by (4) while the FONC for product R&D is given by (22)

$$\left[\sum_{k=t}^{n-1} \beta^{k-t} \{p_2(x_k, s_{k+1}) - I'(s)\} x_k M_k \right] a_t^Q g'(r_t^Q) = 1; t \in \{0, \dots, n-1\} \quad (22)$$

where in either case, $x_t = x(s_{t+1}, c_{t+1})$ for $t \in \{0, \dots, n-1\}$.

Proceeding as in the proof of Proposition 2, the result follows. \blacksquare

Proof of Corollary 4(b), Proposition 2(i): In this case,

$$\frac{g'(r_t^C)}{g'(r_t^Q)} = \frac{\sum_{k=t}^{n-1} \beta^{k-t} [F^{-1}(1-x_k) - c_{k+1} I'(s_{k+1})] x_k M_k}{\mu \sum_{k=t}^{n-1} \beta^{k-t} I(s_{k+1}) x_k M_k}; t \in \{0, \dots, n-1\} \quad (23)$$

Hence for $t \in \{0, \dots, n-2\}$,

$$\frac{g'(r_t^C)}{g'(r_t^Q)} - \frac{g'(r_{t+1}^C)}{g'(r_{t+1}^Q)} = x_t M_t \frac{[\sum_{k=t+1}^{n-1} \beta^{k-t} \{Z_t I(s_{k+1}) - Z_k I(s_{t+1})\} x_k M_k]}{\mu (\sum_{k=t}^{n-1} \beta^{k-t} I(s_{k+1}) x_k M_k) (\sum_{k=t+1}^{n-1} \beta^{k-t} I(s_{k+1}) x_k M_k)} \quad (24)$$

where $Z_k = [F^{-1}(1-x_k) - c_{k+1} I'(s_{k+1})]$, $k \in \{0, \dots, n-1\}$.

Since θ is uniformly distributed, $F^{-1}(1-x_k)$ can be explicitly computed in terms of (s_{k+1}, c_{k+1}) . I find that $x(s_{k+1}, c_{k+1}) = \frac{\theta_2 s_{k+1} - c_{k+1}}{2(\theta_2 - \theta_1) s_{k+1}}$; $F^{-1}(1-x) = \theta_1 + (\theta_2 - \theta_1)(1-x)$. Using these, some algebraic manipulation yields that for $k \in \{0, \dots, n-1\}$, $Z_k = \frac{\theta_2}{2} + \frac{c_{k+1}}{s_{k+1}} (\frac{1}{2} - I'(s_{k+1}) s_{k+1})$. If $I'(s_t) s_t$ is a constant $\in (0, \frac{1}{2}) \forall t \in \{0, \dots, n-1\}$, then using (24) and proceeding as in the proof of Proposition 2, it follows that S_t^{proc} is increasing in t . This gives the sufficient condition stated in the result. ■

Proof of Corollary 5, Proposition 2(i): In this case for $t \in \{0, \dots, n-1\}$,

$$\frac{g'(r_t^C)}{g'(r_t^Q)} = \frac{\sum_{k=t}^{n-1} \beta^{k-t} [F^{-1}(1-x_k) x_k M_k + \{p(x_k, s_{k+1}) - c_{k+1}\} x_k M'_k(s_{k+1})]}{\mu \sum_{k=t}^{n-1} \beta^{k-t} x_k M_k} \quad (25)$$

Hence for $t \in \{0, \dots, n-2\}$,

$$\frac{g'(r_t^C)}{g'(r_t^Q)} - \frac{g'(r_{t+1}^C)}{g'(r_{t+1}^Q)} = x_t M_t \frac{[\sum_{k=t+1}^{n-1} \beta^{k-t} \{Y_t - Y_k\} x_k M_k]}{\mu (\sum_{k=t}^{n-1} \beta^{k-t} x_k M_k) (\sum_{k=t+1}^{n-1} \beta^{k-t} x_k M_k)} \quad (26)$$

where $Y_k = [F^{-1}(1-x_k) + \{p(x_k, s_{k+1}) - c_{k+1}\} \frac{M'_k(s_{k+1})}{M_k(s_{k+1})}]$, $k \in \{0, \dots, n-1\}$.

Since θ is uniformly distributed, x_t , $F^{-1}(1-x_t)$ and $p(x_t, s_{t+1})$ can be computed in terms of (s_{t+1}, c_{t+1}) - see proof of Corollary 4(b), Proposition 2(i). Using these, some algebraic manipulation yields that for $k \in \{0, \dots, n-1\}$, $Y_k = \frac{\theta_2}{2} [1 + \frac{s_{k+1} M'_k(s_{k+1})}{M_k(s_{k+1})}] + \frac{c_{k+1}}{2s_{k+1}} [1 - \frac{s_{k+1} M'_k(s_{k+1})}{M_k(s_{k+1})}]$. If $\frac{s_{k+1} M'_k(s_{k+1})}{M_k(s_{k+1})}$ is a constant $\in (0, 1)$, $\forall t \in \{0, \dots, n-1\}$, then using (26) and proceeding as in the proof of Proposition 2, it follows that S_t^{proc} is increasing in t . This gives the sufficient condition stated in the result. ■

Proof of Corollary 6, Proposition 2: In this case,

$$\frac{g'(r_t^C)}{g'(r_t^Q)} = \frac{[\sum_{k=t}^{n-1} \beta^{k-t} p_2(x_k, s_{k+1}) x_k M_k]}{[\sum_{k=t}^{n-1} \beta^{k-t} x_k M_k] \mu t}; t \in \{0, \dots, n-1\} \quad (27)$$

Proceeding as in the proof of Proposition 2 yields, for $t \in \{0, \dots, n-1\}$

$$\begin{aligned}
\frac{g'(r_t^C)}{g'(r_t^Q)} &= \frac{g'(r_{t+1}^C)}{g'(r_{t+1}^Q)} \\
&+ \frac{\sum_{k=t+1}^{n-1} \sum_{k'=t+1}^{n-1} \beta^{k-t} \beta^{k'-t} x_k x_{k'} M_k M_{k'} p_2(x_k, s_{k+1}) [\mu_{t+1} - \mu_t]}{A_t} \\
&+ \frac{\sum_{k=t+1}^{n-1} \beta^{k-t} x_t x_k M_t M_k [\{p_2(x_t, s_{t+1})\} \mu_{t+1} - \{p_2(x_k, s_{k+1})\} \mu_t]}{A_t}
\end{aligned} \tag{28}$$

where $A_t = [\sum_{k=t}^{n-1} \beta^{k-t} x_k M_k] [\sum_{k=t+1}^{n-1} \beta^{k-t} x_k M_k] \mu_t \mu_{t+1}$.

Since μ_t is increasing in t and $p_2(x_t, s_{t+1})$ is decreasing in t in Case D and is a constant in Case S, using (28) and proceeding as in the proof of Proposition 2 the result follows. \blacksquare

Proof of Corollary 7, Proposition 2(i): Here, the fringe always charges a price of c_f and sells a product of quality s_f . Hence, all consumers with $\theta \geq \frac{c_f}{s_f}$ buy the product. Suppose in period t , the R&D firm sells a product of quality s_{t+1} . If it charges a price $P > c_f + (\frac{c_f}{s_f})(s_{t+1} - s_f)$, total quantity sold is $[1 - F(\frac{c_f}{s_f})]M_t$, quantity sold by the dominant firm is $[1 - F(\frac{P - c_f}{s_{t+1} - s_f})]M_t$ and the rest is sold by the fringe. On the other hand, if the R&D firm charges a price $P \leq c_f + (\frac{c_f}{s_f})(s_{t+1} - s_f)$, total quantity sold is $[1 - F(\frac{P}{s_{t+1}})]M_t$ and is sold by the R&D firm and the fringe sells nothing.

Hence, in this case the R&D firm solves the dynamic optimization problem defined by equations (1)-(3); the only difference being that $p(x, s) = c_f + (s_{t+1} - s_f)F^{-1}(1 - x)$ if $x < 1 - F(\frac{c_f}{s_f})$ while it is $s_{t+1}F^{-1}(1 - x)$ as in my original set-up if $x \geq 1 - F(\frac{c_f}{s_f})$. Here, if the R&D firm finds it optimal to choose $x \geq 1 - F(\frac{c_f}{s_f})$, then it behaves like a monopolist as in my original set-up and hence the result goes through. If the R&D firm finds it optimal to choose $x < 1 - F(\frac{c_f}{s_f})$, the assumptions guarantee that $MR(x, s)$ is positive for any such x and the result follows by the same argument as for Proposition 2(i). \blacksquare

Proof of Proposition 3: Case D: The optimization problem for firm W is the same as that of a price-discriminating monopolist. Hence, (a) follows from Corollary 1, Proposition 2.

In (b), product or process R&D does not lead to any change in output. Hence, the FONC for process and product R&D for firm P are given by equations (4) and (5) respectively with $\frac{Q_t}{M_t}$ replacing x_t throughout. Firm W maximizes

$$\sum_{k=0}^{n-1} \beta^k [M_k U_k + \{s_{k+1} F^{-1}(1 - \frac{Q_k}{M_k}) - c_{k+1}\} Q_k - r_{k,W}^Q - r_{k,W}^C]$$

where $U_k = \int_{F^{-1}(1 - \frac{Q_k}{M_k})}^{\theta_2} [\theta - F^{-1}(1 - \frac{Q_k}{M_k})] f(\theta) d\theta$; $k \in \{0, \dots, n-1\}$, s_{t+1} and c_{t+1} for any $t \in \{0, \dots, n-1\}$ are determined as usual by the R&D effort of firm W in period t and in prior periods.

From the dynamic optimization problem of firm W above, it follows that for any $t \in \{0, \dots, n-1\}$, its FONC for process R&D is the same as that for firm P while its FONC for product R&D is given by $[\sum_{k=t}^{n-1} \beta^{k-t} \{Q_k F^{-1}(1 - \frac{Q_k}{M_k}) + M_k U_k\}] a_t^Q g'(r_{t,W}^Q) = 1$.

Comparing the FONC's for process and product R&D for firms W and P , (b) follows.

From the FONC's for product R&D for firms W and P , it follows that for any $t \in \{0, \dots, n-2\}$,

$$\frac{g'(r_{t+1,P}^Q)}{g'(r_{t+1,W}^Q)} - \frac{g'(r_{t,P}^Q)}{g'(r_{t,W}^Q)} = \frac{M_t [\sum_{k=t}^{n-1} \beta^{k-t} M_k \{x_t U_k F^{-1}(1 - x_t) - x_k U_t F^{-1}(1 - x_k)\}]}{(\sum_{k=t}^{n-1} \beta^{k-t} x_k M_k F^{-1}(1 - x_k)) (\sum_{k=t+1}^{n-1} \beta^{k-t} x_k M_k F^{-1}(1 - x_k))} \quad (29)$$

Since, θ is uniformly distributed, (29) can be explicitly calculated. This yields that for any $t \in \{0, \dots, n-2\}$,

$$\frac{g'(r_{t+1,P}^Q)}{g'(r_{t+1,W}^Q)} - \frac{g'(r_{t,P}^Q)}{g'(r_{t,W}^Q)} = \frac{M_t [\sum_{k=t+1}^{n-1} \beta^{k-t} \frac{M_k (\theta_2 - \theta_1)^2 x_t}{2} \{x_k^2 F^{-1}(1 - x_t) - x_k x_t F^{-1}(1 - x_k)\}]}{(\sum_{k=t}^{n-1} \beta^{k-t} x_k M_k F^{-1}(1 - x_k)) (\sum_{k=t+1}^{n-1} \beta^{k-t} x_k M_k F^{-1}(1 - x_k))} \quad (30)$$

Since x_t is increasing in t , it follows from (30) that $g'(r_{t,P}^Q)/g'(r_{t,W}^Q)$ is increasing in t . Hence, from the functional form of $g()$, (c) follows.

(d) follows from the fact that with a general subsidy, the FONC's for product and process R&D for firm P are as in (b) except for the modification that $(1 - \delta)$ replaces 1 on the right hand side of each equation.

Case S: In this case, FONC for process and product R&D for both firm W and firm P are given by (4) and (5) respectively with $F^{-1}(1 - \frac{Q_k}{M_k})$ always equalling θ . The result follows from proceeding as in the proof of Proposition 2(ii). ■

Proof of Proposition 4: Here, all variables for firm i have a subscript i .

Claim: In each of the three cases, $\frac{g'(r_{t,1}^C)}{g'(r_{t,1}^Q)} > \frac{g'(r_{t,2}^C)}{g'(r_{t,2}^Q)}$.

Proof of Claim: From (4) and (5), it follows that

$$\text{In Cases (a) and (b): } \frac{g'(r_{t,i}^C)}{g'(r_{t,i}^Q)} = \frac{F^{-1}(1 - x_{t,i})}{\mu t}; i \in \{1, 2\} \quad (31)$$

Case (a): Since both firms sell the same amount, $x_{t,1}M_{t,1} = x_{t,2}M_{t,2}$. Since, $M_{t,1} > M_{t,2}$, $x_{t,1} < x_{t,2}$. Hence the claim holds.

Case (b): Since $M_{t,1} = M_{t,2}$, $x_{t,1} = x_{t,2}$. From the underlying assumption here, it follows that the claim holds.

Case (c): Since $\beta \neq 0$ for firm 2,

$$\frac{g'(r_{t,2}^C)}{g'(r_{t,2}^Q)} = \frac{\sum_{k=t}^{n-1} \beta^{k-t} F^{-1}(1 - x_{k,2}) x_{k,2} M_{k,2}}{\mu_t \sum_{k=t}^{n-1} \beta^{k-t} x_{k,2} M_{k,2}} \quad (32)$$

Rearranging terms, this can be expressed as

$$\frac{g'(r_{t,2}^C)}{g'(r_{t,2}^Q)} = \frac{F^{-1}(1 - x_{t,2})}{\mu_t} + \frac{\sum_{k=t}^{n-1} \beta^{k-t} \{F^{-1}(1 - x_{k,2}) - F^{-1}(1 - x_{t,2})\} x_{k,2} M_{k,2}}{\mu_t \sum_{k=t}^{n-1} \beta^{k-t} x_{k,2} M_{k,2}} \quad (33)$$

Since, $\beta = 0$ for firm 1, $g'(r_{t,1}^C)/g'(r_{t,1}^Q)$ is given by (31). Since $M_{t,1} = M_{t,2}$ and both firms sell the same amount, $x_{t,1} = x_{t,2}$. Also by Lemma 3, $x_{t,2}$ is increasing in t . Hence comparing (31) and (33), it follows that the claim holds.

The result follows from the claim and the logic underlying the proof of Proposition 2. ■

Proof of Corollary 1, Proposition 4 Case (c): Using the FONC's for process and product R&D - these are as in Section 4.2.6 - and proceeding as in the proof of Proposition 4, the result follows. ■

Proof of Proposition 5: (a) Since firm 1 produces more than firm 2, from (4) and diminishing returns to R&D, (i) follows. Also, since firm 1 produces more than firm 2, $x_1 > x_2$. Since, per-unit cost of production is non-negative, both firms choose x such that $\text{MR}(x,s)$ is positive. From A1, it follows that $x F^{-1}(1 - x)$ is increasing in x over the range of x for which $\text{MR}(x,s)$ is positive. Since, $x_1 > x_2$, from (5) (ii) follows. Also, in this case $g'_t(r_{t,i}^C)/g'_t(r_{t,i}^Q)$, $i \in \{1, 2\}$, is given by (31). Since, $x_1 > x_2$, by the logic underlying the proof of Proposition 2, (iii) follows.

(b) From the functional form of $g()$, it follows that $\frac{g(r)}{r}$ is decreasing in r . Hence, from (a.i) and (a.ii), (b.i) and (b.ii) follow. ■

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