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# Operationalizing technology improvements in product development decision-making

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## Abstract

Achieving competitive advantage and price premiums in many technology-based markets requires the incorporation of current technology in new products. To do so, firms in hyper-competitive environments increasingly plan and design their products concurrent with the independent development and validation of underlying technologies. Simultaneous validation of a core technology has important implications for a company's product positioning and launch sequence decisions making these traditional marketing decisions relevant to operations managers. Prior research has shown that to minimize cannibalization in the absence of such improvements in technology, a firm should not launch low-end products before high-end products. However, concurrent evolution of technology can make it desirable and even necessary to introduce low-end products before high-end products. This is because in technology-based industries, improvements in technology delay the introduction of a high-end product, and a firm must trade-off the benefit of launching the low-end product earlier (greater discounted profits) against the cost of cannibalization of high-end product sales. High-end product cannibalization can be further reduced by offering the customer an option to upgrade from the low-end to high-end product, with important implications for the firm's product positioning and introduction sequence decisions. Based on our study in the high technology industry, we model the product positioning and introduction sequence decisions under the simultaneous evolution of technology. Our analysis indicates that it may be optimal in a variety of circumstances for a firm to launch products in an increasing order of performance, even in the absence of network externalities. Besides presenting analytical results for product positioning and profit from different introduction sequences, the paper also makes a contribution to managerial practice by providing insights in the form of a conceptual framework.

*Keywords:* Product development; New product series; Introduction sequence

## 1. Introduction

Leading firms in the personal computer (PC) industry such as Dell and Compaq have lately been announcing the introduction of their new higher-performance products on the same day their processor supplier (Intel) announces the introduction of its higher-performance microprocessor technology to the market. This is achieved by the computer firms developing their products *concurrently* with the development and validation of microprocessors at Intel. Due to the technological challenges involved in developing processors, Intel introduces the processor technology in an increasing order of performance: beginning with slower microprocessors in a new family (such as Pentium), and gradually evolving to a higher performance technology (see Fig. 1). This sequential upward progression is also reflected in the introduction of computer products and other high-technology peripherals (such as hard drives, digital signal processors, and even software). However, this recent trend is contrary to the pattern observed in other industries such as books, movies, automobiles and even PCs in the 1980s. As Moorthy and Png (1992) note, book publishers introduce hardcover books before paperbacks, and IBM released its lower-performance PS/1 several years after the introduction of its higher-end PS/2 system.

The rationale for delaying low-end products is to minimize the cannibalization of the high-end products, and was the thrust of the discussion in the pioneering work of Moorthy and Png (1992). However, the recent trend in the high-technology industry of introducing products in an increasing order of performance (low-end products before high-end) indicates that additional (operational) factors may be at work in making the product introduction decision. In particular, the concurrent development of technology places operational limits on the earliest time by which a high-end product can be introduced. In such cases, delaying the low-end product may minimize cannibalization of the high-end product, but also would lower the discounted profit accruing to the firm. This is the one of the marketing-operations trade-offs that we model in the paper to determine the profit maximizing product positioning and introduction sequence.

One approach a firm may use to mitigate cannibalization of high-end product is to design the product so as to offer the customer the option to upgrade from the low-end product to high-end product. Such a design approach ensures that customers with the highest valuation for performance can enjoy the low-end product earlier and then upgrade to the high-end product as soon as it is available. The firm can also earn a greater profit by charging the customer a premium for the upgrade. As we observe in the paper, the upgrade option however changes the optimal product location and the level of market coverage offered by the firm.

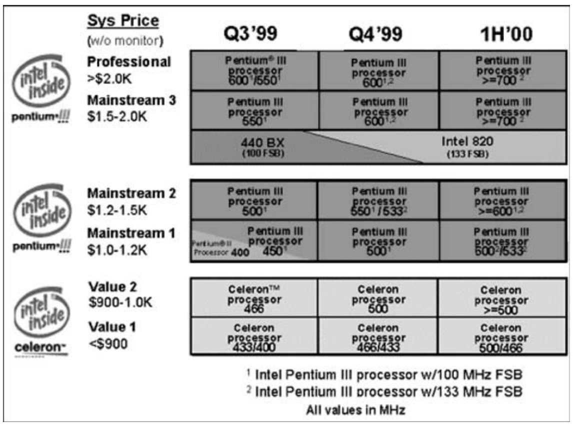


Fig. 1. Intel's technology introduction sequence for 1999–2000 (from: http://channel.intel.com/business/iachan/micinfo/desktop/tdroadmap.htm).

Product positioning and introduction sequence decisions are particularly important to firms that develop technology-based products such as PC's and telecommunication devices. The evolution in time of the performance of the underlying technology (for example microprocessors) determines how early the product of a certain performance level can be introduced to the market. In this context, the research questions that we address in this paper are as follows:

(I) How should a firm facing exogenous technology improvements and designing products concurrently with the evolving technology determine the performance levels, target market segments, and order of introduction for its products?
(II) What impact does offering the consumer the option to upgrade have on the above decisions?
(III) How do declining prices under competition influence product positioning and introduction sequence? How should two competing firms determine the performance levels and prices of their products?

Positioning and introduction sequence decisions have been studied by several economics and marketing researchers including Mussa and Rosen (1978), Spence (1980), and Moorthy (1984). Spence (1980) deals with the positioning of a product family in a market with quantity-dependent pricing, but does not consider the issues of different launch sequences or technology improvement over time. Mussa and Rosen (1978) and Moorthy (1984) address the issues of product positioning and market segmentation, by considering the tradeoff between an increased unit variable cost for products of higher performance and the higher margins that high-end customers would be willing to pay. However, they do not model the sequence of introduction, instead they assume all products are launched simultaneously. Wilson and Norton (1989) address the timing of introduction of a new product extension considering the degree of diffusion of the previous generation and finding the optimal launch timing based on margins, however our approach relies on segmenting the same market while minimizing the impact of cannibalization. Dhebar (1994) identifies the conditions for the existence of subgame-perfect equilibria for different launch sequences, but does not consider the dynamics of technology improvement and its effects on the introduction sequence.

Moorthy and Png (1992) present an insightful model of the trade-offs underlying launch sequence decisions. They compare the merits of sequential and simultaneous launch for a market with two customer segments of pre-specified sizes and with no exogenous improvements in technology. It is therefore possible to launch both the higher-end and lower-end product simultaneously at any given period, however doing so would cannibalize the demand for the higher-end product. While it is optimal to introduce high-end products before low-end products when cannibalization is strong, it is not desirable under the framework of their model to ever launch the low-end product before the high-end product. Because we consider operational issues of products being developed based on a concurrently-evolving technology, it is not possible to launch the product of a certain level of performance before a certain period of time (when the technology necessary is available). Under these conditions, we find that introducing products in an increasing order of performance may be optimal in a range of situations (complementing the result of Padmanabhan et al. (1997)). Our model is also more general than that of Moorthy and Png (1992) in that we consider a general distribution of customer preferences. We also do not assume the existence of two segments of known sizes, instead the market segments and their sizes are explicitly derived from our model. However, we do follow the tradition of Moorthy and Png (1992) and other economics research in assuming in many cases that a firm can credibly commit to the launch and performance levels of higher-end products. This reflects the product development trend in the high-technology industry, where PC firms set a schedule of product launch based on Intel's processor launch plans. We also analyze some special cases where no credible commitment may be issued by the firm, and study the impact on the positioning of the products.

Recently, there has been considerable work on the operational issues surrounding product development decisions (Joglekar, 1999). Ahmadi and Wang (1999) model the design interdependence issues facing the rationalization of product development processes. Kim and Chhajed (2000) present an interesting model to illustrate the cost-saving benefits of a common component using a model structure similar to that of Moorthy and Png (1992). Smith and Eppinger (1997) study the dynamics of design iterations and show how they can be analytically formulated. Thomke and Bell (2001) model the trade-off between the cost of prototyping and the cost of re-design to derive optimal policies for prototyping in product development.

Based on our study of the high-technology industry, we present a model that integrates operational and marketing factors such as performance improvement over time, cannibalization, diverse consumer valuations, firm and consumer discounting, and competitive assessment. The model formulation helps us identify analytical results for optimal product performances, prices, and target market segments. We also characterize the domain of appropriateness of different orders of introduction (such as sequentially increasing order of performance, sequentially decreasing order of performance or simultaneous introduction). Based on the model results, we present a managerial framework to provide a summary of the model insights. One interesting finding of this work is that introducing products in an increasing order of performance is desirable when the performance of products can be improved by adopting concurrently evolving technology. We also find that designing the product to offer customers the upgrade option increases the domain of optimality of sequential upward introduction. When providing the upgrade option, if a firm intends to offer an upgrade to the customers later, it is better not to pre-announce the product. However, if the firm does not intend to introduce the upgrade, it is better to pre-announce the high-end product, so that some consumers will wait for the high-end product to be introduced, and pay the higher margins associated with the high-end product. Under a duopoly, the approach of sequential upward introduction again becomes even more attractive. We also obtain interesting results for the market share and profit of two competing firms in a duopolistic environment, with the low-end firm increasing its profit and the high-end firm facing a decrease in its profit compared to the monopoly situation.

The rest of this paper is organized as follows. We discuss the model conceptualization and formulation in Section 2. In Section 3, we present analytical results for the monopoly case when the customer does not have the option to upgrade to a higher-performance product. In Section 4, we analyze both the effect of offering the customer an option to upgrade and a competitive environment on the firm's product positioning and introduction sequence decisions. After proposing a conceptual framework to summarize the insights from the model in Section 4, we conclude in Section 5 with the strengths and limitations of the model, and avenues for future research.

## 2. Model setting and conceptualization

We discuss the model conceptualization and assumptions in this section. For ease of exposition, we begin by describing a monopolistic environment.

The firm that is our focus is planning the development and launch of a technology-based product, which is assumed to be differentiated along a single attribute (a primary dimension, for example processor speed in the case of computers) referred to as *performance quality*. We denote the performance quality level of product $i$ on this dimension by $q_i$. For the analysis in Section 3, we assume that consumers buy just one product, and leave the market after purchase. In Section 4, we consider the case where consumers who buy the product at a given time would be interested in upgrading to a higher performance product at a later period.

The performance of the product is realized using an exogenous underlying technology $T$ that is being concurrently developed. Due to this concurrent development, the maximum performance level that the product can deliver improves with time (see Fig. 2). Therefore, our model of product development effort extends through the life-cycle of the core technology. As described in Section 1, the firm makes decisions on the performance levels of individual products and their sequence of introduction. Because the precise timing of introduction is not as much of a focus as the insights on the relative order of introduction of the

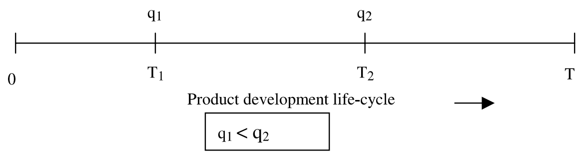


Fig. 2. Constraint on maximum deliverable performance.

products, we use a simple multi-period model of product introduction. We first model the case where the firm introduces only two products, one at a lower performance level and another at a higher performance level, referred to as the low-end product and high-end product, respectively.

We model the unit variable cost of the product to be an increasing and convex function of the product's performance quality $q_i$. In other words, the marginal cost of delivering higher performance increases with the level of performance. Specifically, we assume the unit cost of product $i$ to be independent of demand volume and is given by $cq_i^2$, where $c$ is a constant. This form of the unit cost offers the added benefit of tractability, and is also used in the literature (Moorthy, 1984; Moorthy and Png, 1992). We also assume that the fixed costs of developing products are negligibly small compared to the gross profit, since the products are introduced in the mass market.

To model demand, we assume consumers to be rational in that they purchase the product with a performance level that maximizes their net utility surplus. Owing to differences in needs, perception of performance, and extent of usage of the product, different consumers value a unit of performance differently, which we model in a fashion similar to established literature (Mussa and Rosen, 1978; Spence, 1980; Moorthy and Png, 1992). Each consumer has a certain valuation of performance, denoted by $v$, which is the amount the consumer is willing to pay for a unit of performance. For product $i$ which has a performance quality of $q_i$, a customer with a valuation of $v$ is willing to pay a maximum of $vq_i$. If a consumer has a higher valuation for performance, s/he would gain more utility, and would be willing to pay more for a unit of product performance. The linear form of consumer utility is commonly used in the literature, because it enables a simpler analysis of consumer choice. The surplus that a consumer with valuation $v$ derives from a product of performance quality $q_i$ is given by $vq_i - p_i$, where $p_i$ is the price of the product. Let $F(v)$ denote the cumulative number of consumers with valuation less than or equal to $v$, and let the mass density function of the valuation $v$ be given by the distribution function $f(v)$. [1] We assume that $f(v)$ and $F(v)$ are known a priori to the firm.

The surplus derived by the consumer from a product is also a function of the time of consumption, as a product offered earlier provides greater utility than a product with the same performance offered later. In other words, consumers discount the surplus accrued from a product at the rate of $\delta_c$; the discounted surplus from product $i$ introduced in period $n$ to a consumer with a valuation of $v$ is given by $\delta_c^n(vq_i - p_i)$. The firm too prefers early accrual of profits, and it discounts profits from products at a rate of $\delta_s$.

As is the case in the high technology industry, we model that the firm communicates the roadmap of its products (timing of introduction and the performance levels of the products) to its consumers. We also assume in some sections that this announcement is credible, i.e., consumers will wait to purchase the product that is introduced later if their discounted surplus from that product is higher. This ensures that there exists subgame-perfect equilibria, i.e., the later product is launched at a performance level $q$ and price $p$ that is expected by the customer (Dhebar, 1994). For some special cases for the distribution of the consumer valuations, we analyze the positioning problem where a credible announcement cannot be made.

[1] We assume here that $v$ has a continuous distribution over the entire market. Since the product family is designed for the mass market, this is a reasonable assumption.

Table 1
Operational aspects of product availability using different introduction sequences

| Introduction sequence | Period I | Period II | Period III |
|---|---|---|---|
| Upward sequential introduction | Low-end product | High-end product | |
| Downward sequential introduction | | High-end product | Low-end product |
| Simultaneous introduction | | Low-end product; High-end product | |

The concurrent development of the core technology means that (a) highest deliverable performance of products increases over time, and (b) certain high levels of technology may not be available earlier in time and higher performance products must wait until the appropriate level of technology becomes available.

The operational issues surrounding product availability is modeled in this paper by constraining the earliest period in which the high-end product can be introduced. For our analysis with two products, we use a three-period model, in which the high-end product can be introduced no earlier than the second period, while the low-end product can be introduced as early as the first period. If the firm introduces products in a sequentially downward fashion (delaying the low-end product by a period to limit cannibalization), it can introduce the low-end product only in the third period after the launch of the high-end product in the second period. Table 1 shows product availability for the three introduction approaches: (1) upward sequential introduction (low-end product followed by high-end), (2) downward sequential introduction (high-end product followed by low-end), and (3) simultaneous introduction of both products.

It is evident from the above table that upward sequential introduction leads to early accrual of profit, but also results in increased cannibalization of the high-end product. When a low-end product is introduced early in the market, the firm has to ensure that it does not cannibalize the sales of the high-end product to a large extent, and the firm can reduce the extent of cannibalization by pricing the two products appropriately, and differentiating the products in terms of performance quality levels. When the firm and the consumer discount their profits and utilities respectively at different rates, the profits and the costs of cannibalization can be manipulated appropriately, depending on the rates of discounting used by the firm and the consumers. In our analyses, we incorporate these factors to identify the regions where each of the three sequential introduction strategies are optimal, and provide insights for the firm for planning the product development process. The three introduction sequences are analyzed in the next section to derive expressions for performance quality levels and firm profitability.

## 3. Model formulation and solution for a two-product family

We now present the detailed model formulation and solution when the family consists of two products. In this section, we assume that the firm can make a credible announcement about the relative performances of the two products. The performance and price of the low-end product are denoted by $q_1$ and $p_1$, respectively, and that of the high-end product are denoted by $q_2$ and $p_2$. Since consumers with higher valuations of performance are willing to pay more for a product, the firm targets the higher-end product at these consumers. Consumers with lower valuations of performance either adopt the low-end product, or do not purchase any product. We also assume that all consumers will purchase just one product (this assumption is relaxed when the upgrade option is offered). The two market segments are characterized by the variables $v_1$ and $v_2$ (see Fig. 3), whose significance is as follows:

- Consumers with a valuation lower than $v_1$ do not buy any of the products, as the utility $v_i q_i$ they derive from a product is less than $p_i$, the price of the product.

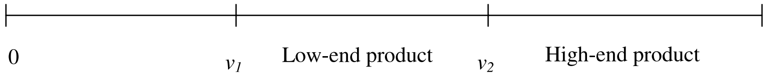


Fig. 3. Consumer valuations who adopt each of two products.

- Consumers with valuations between $v_1$ and $v_2$ buy the low-end product, as they get a higher surplus from the low-end product than the high-end product.
- Consumers with valuations higher than $v_2$ derive the maximum surplus from the high-end product, and consequently buy the higher end product. [2]

The demand volume for the low-end product is simply $F(v_2) - F(v_1)$, as every customer whose valuation lies between $v_1$ and $v_2$ purchases the low-end product. Similarly, the demand volume for the high-end product is given by $1 - F(v_2)$. The profit maximization problem for the three introduction approaches in Table 1 can be formulated mathematically as Problem TP.

*Problem TP*

$$\text{Max}\,\Pi = \gamma_s[\{F(v_2) - F(v_1)\}(p_1 - cq_1^2)] + \mu_s[\{1 - F(v_2)\}(p_2 - cq_2^2)]$$

such that:

$$\gamma_c(vq_1 - p_1) \geqslant \mu_c(vq_2 - p_2), \quad v_1 \leqslant v < v_2 \tag{1}$$

$$\gamma_c(vq_1 - p_1) \leqslant \mu_c(vq_2 - p_2), \quad v_2 < v \leqslant \infty \tag{2}$$

$$vq_1 - p_1 \geqslant 0, \quad v_1 \leqslant v \leqslant v_2 \tag{3}$$

$$vq_2 - p_2 \geqslant 0, \quad v_2 < v \leqslant \infty \tag{4}$$

The objective function $\Pi$ (firm's profit) is the sum of two terms representing the contributions from the low-end product and the high-end product. The profit of each product is equal to the demand volume multiplied by the margin (which is equal to $p - cq^2$), and is discounted by factors $\gamma_s$ and$\mu_s$ which correspond respectively to the period of introduction of the low-end and high-end product, respectively. Constraints 1 and 2 are the self-selection constraints, which ensure that the consumers select (get more surplus from) the products targeted at them. Constraints 3 and 4 are the participation constraints, and they ensure that the utility that the consumers obtain from the product is positive. $\gamma_c$ and $\mu_c$ are the appropriate consumer discounting factors for the utilities derived from the low-end product and high-end product, respectively. These and the firm discounting factors are based on the period of introduction, for example, if the low-end product is introduced in the first period, $\gamma_s$, and $\gamma_c$ are equal to 1.

### *3.1. Model analytical solution*

In this section, we characterize the optimal solution when consumer valuations have general distributions. The analytical solution uses the notion of the *marginal consumer* (Mussa and Rosen, 1978; Besanko and Winston, 1990). Consumers with valuations of $v_1$ and $v_2$ in Fig. 3 are the marginal consumers in the market, as they are indifferent between the two options that they have. The consumer with a valuation of $v_1$ for performance is indifferent between buying and not buying the low-end product, and the consumer with

[2] The reason for such a market structure is as follows. Consumers with very low valuations of quality (low $v$) will not be willing to pay for either product as their reservation price, given by $vq$, is low. If a consumer with a valuation of $v_1$ buys the low-end product, then a consumer with a higher valuation (who derives greater utility) will also buy the low-end product. Consumers with very high valuations of quality will buy the high-end product even if it is more expensive, because the excess utility from quality $v(q_2 - q_1)$ is higher than the difference in the prices of the products $p_2 - p_1$.

a valuation of $v_2$ is indifferent between buying the low-end product and the high-end product. Equating the utilities of the marginal from their two options gives us the optimal prices. From Eqs. (1)–(3), we obtain

$$p_1 = v_1 q_1$$
$$p_2 = v_2 q_2 - \frac{\gamma_c}{\mu_c}(v_2 - v_1) q_1$$

Thus the surplus of the lower-end marginal consumer (with a valuation of $v_1$) equals zero, since s/he is the customer with the lowest valuation to buy the product. $p_2$ is obtained by setting the utility of the higher-end marginal consumer (with a valuation of $v_2$) from the high-end product equal to his utility from the low-end product.

For the purpose of extracting insights, we suppose that the firm operates in a perfect capital market (Besanko and Winston, 1990), i.e. the firm and the consumer have the same rate of discounting ($\gamma_s = \gamma_c = \gamma$, $\mu_s = \mu_c = \mu$). While the model analysis can be carried out in the non-capital market case, it is tedious and results in cumbersome expressions. We discuss the case of non-capital markets in Section 3 for specific conditions on valuations. Under this assumption, the optimal values of $q_1$ and $q_2$ are given by

$$q_1 = \frac{v_1}{2c} - \frac{v_2 - v_1}{2c}\frac{1 - F(v_2)}{F(v_2) - F(v_1)}, \quad q_2 = \frac{v_2}{2c}$$

This gives us

$$\Pi(q^*, v) = \frac{\gamma}{4c}\frac{[v_2 F(v_2) - v_1 F(v_1) - (v_2 - v_1)]^2}{F(v_2) - F(v_1)} + \frac{\mu}{4c} v_2^2 [1 - F(v_2)] \tag{5}$$

Eq. (5) can also be equivalently re-written as:

$$\Pi(q^*, v) = \gamma[F(v_2) - F(v_1)] c q_1^2 + \mu[1 - F(v_2)] c q_2^2 \tag{6}$$

Equation (6) gives us some interesting insights. The first and second terms represent the profit from the low-end and high-end segments, respectively. Note how the un-discounted profit from each segment equals the cost of goods sold to that segment (or the product of the size of the segment and the unit variable cost). The boundary valuations $v_1$ and $v_2$ are as in Result 1.

**Result 1**

The optimal values of $v_1$ and $v_2$ are given by

$$v_1^* = \frac{2}{r_1} - \frac{2}{r_2}\frac{\gamma}{\mu}\frac{1 - F(v_2^*)}{1 - F(v_1^*)} \tag{7}$$
$$v_2^* = \frac{2}{r_1} - \frac{2}{r_2}\frac{\gamma}{\mu}\frac{1 + F(v_1^*) - 2F(v_2^*)}{1 - F(v_1^*)} \tag{8}$$

where

$$r_1 = \frac{f(v_1^*)}{1 - F(v_1^*)} \quad \text{and} \quad r_2 = \frac{f(v_2^*)}{1 - F(v_2^*)}.$$

The proof of Result 1 is based on the method used in Moorthy and Png (1992) and is provided in the appendix, which is available with the authors. It is interesting to note that the expressions for $r_1$ and $r_2$ are the hazard rates of the valuation function $f$ evaluated at points $v_1^*$ and $v_2^*$ respectively.

If the firm introduces only a single product, the problem can be analyzed similarly to obtain $p^* = v^* q^*$, $q_* = v^*/2c$, and $v^* = (2/r^*)$. Comparing the optimal valuations for the single product with that of the two product case (obtained in Result 1), we see that $v_1^* < v^* < v_2^*$ for all distributions of $f(v)$, as expected.

Result 1 reveals a number of interesting aspects of the two-product planning problem. The boundary market valuations $v_1^*$ and $v_2^*$ are determined by a combination of the hazard rates and the market segments for the two products. It is interesting to note that the optimal market segment for the single product problem is given by $v^* = (2/r^*)$ where $r^*$ is the hazard rate at $v^*$. In this case, the hazard function at $v^*$ is an indicator of the density of consumers per unit market potential with valuations higher than $v^*$. This result is similar to results in renewal theory, in that a high-end product is introduced when the remaining market for the low-end product tends to result in lower margins. [3]

### *3.2. Analytical solution for uniformly distributed consumer valuations*

In the last section, we considered the case of general distributions of consumer valuations and derived expressions for optimal prices and performance levels. Now, we consider the special case when consumer valuations are uniformly distributed, and obtain closed-form expressions for the optimal performance qualities, prices, and market segment boundaries. The uniform case has been used by other researchers in the literature to derive insights (Besanko and Winston, 1990; Dhebar, 1994), and is particularly suitable when the consumer distribution along the performance space cannot be predicted exactly (due to non-informative priors). For the sake of generality, we let the upper bound of the uniform distribution to be a parameter U (instead of constraining it to 1).

#### *3.2.1. Credible announcement can be made*

The optimal performance levels, prices and market segments are provided in Result 2. The results for perfectly capital markets are obtained simply by equating the consumer and firm discounting factors.

**Result 2**

*Case 1*: Under simultaneous introduction of the two products, the optimal performance levels are given by $q_1 = (0.2/c)U$ and $q_2 = (0.4/c)U$. The values of the marginal valuations of the consumer segments are given by $v_1 = 0.6U$ and $v_2 = 0.8U$.

*Case 2*: When the two products are introduced in an increasing order of performance, the optimal performance levels are given by

$$q_1 = \frac{v_1 - \frac{\delta_s}{\delta_c}(U - v_2)}{2c} \quad \text{and} \quad q_2 = \frac{v_2}{2c}$$

where $v_1$ and $v_2$ are the values of the marginal valuations of the consumer segments are given by

$$v_1 = \frac{1}{3}\left[\left(2 - \frac{\delta_s}{\delta_c}\right)v_2 + \frac{\delta_s}{\delta_c}U\right]$$

and

$$v_2 = \frac{8(\delta_s/\delta_c)(1+\delta_s/\delta_c)^2 - 18\delta_s - \sqrt{[8(\delta_s/\delta_c)(1+\delta_s/\delta_c)^2 - 18\delta_s]^2 - 16(\delta_s^2/\delta_c^2)(1+\delta_c/\delta_s)[4(1+\delta_s/\delta_c)^3 - 27\delta_s]}}{8(1+\delta_s/\delta_c)^3 - 54\delta_s}U$$

[3] It is interesting to note that if the valuation function was distributed exponentially with $f(x) = e^{-x}$, then the hazard rate is equal to 1 for all values of $x$, since $1 - F(x) = e^{-x}$. Therefore, for the exponential distribution, we get $v_1 = 1.6$, $v_2 = 3.2$, $q_1 = 0.6/c$ and $q_2 = 1.6/c$ in the simultaneous introduction case. If the firm were to introduce a single product, the firm would introduce it with a quality of $q = 1/c$ and all consumers with $v \geqslant 2$ would purchase the product.

*Case 3*: When the two products are introduced in a decreasing order of performance, the optimal performance levels are given by

$$q_1 = \frac{v_1 - \frac{\delta_c}{\delta_s}(U - v_2)}{2c} \quad \text{and} \quad q_2 = \frac{v_2}{2c}$$

where $v_1$ and $v_2$ are the values of the marginal valuations of the consumer segments are given by

$$v_1 = \frac{1}{3}\left[\left(2 - \frac{\delta_c}{\delta_s}\right)v_2 + \frac{\delta_c}{\delta_s}U\right]$$

and

$$v_2 = \frac{8\delta_c(1+\delta_c/\delta_s)^2 - 18 - \sqrt{[8\delta_c(1+\delta_c/\delta_s)^2 - 18]^2 - 16(\delta_c^2/\delta_s)(1+\delta_c/\delta_s)[4\delta_s(1+\delta_c/\delta_s)^3 - 27]}}{8\delta_s(1+\delta_c/\delta_s)^3 - 54}U$$

The role of discounting in affecting the decisions of the firm are well-known, in this case, consumer discounting serves a dual purpose. It models the pace of technological evolution, and it also models the intertemporal utility preferences of consumers (Desiraju and Shugan, 1999; Peart, 2000).

An interesting implication of the above result is that introducing a two-product family in an upward or downward sequential order may, for some consumer and firm discount factors, result in lower profits than the introduction of a single product. This constrains the domain of existence of the sequentially upward and downward introduction approaches. (*The profits accruing from the simultaneous introduction of two products are always higher than that of a single product*, so the simultaneous approach is viable for all values of the discount factors.) The sequentially upward and downward introduction approaches may lead to lower profits than a single product for the following reasons. If firms are much more impatient than their customers ($\delta_s < 2\delta_c$), then introducing products in a decreasing sequence of performance causes the *extra* profit from the low-end product *to be lower than* the reduction in profit of the high-end product due to cannibalization. Similarly, if the firm introduces two products in a market where customers are very impatient ($\delta_c < 0.6$), then customers will not wait for the high-end product, so *the cannibalization of profits* of the high end product are greater than the extra profits from the low-end product, lowering the total profit to the firm.

The discounting rates where the strategies of sequential upward introduction and sequential downward introduction are viable are plotted below in Fig. 4. The simultaneous approach is not shown in the figure as it can be used for all values of $\delta_s$ and $\delta_c$.

By comparing the profits from each of the three introduction sequences, we may determine the regions where each of the three strategies are optimal (shown in Fig. 5).

The cost coefficient $c$ appears in the denominators of both the optimal performance levels $q_1$ and $q_2$, and the prices $p_1$ and $p_2$, but not in the numerators, hence the comparison of profits of all three strategies are independent of $c$. An exhaustive numerical comparison along the two dimensions $\delta_s$ and $\delta_c$, for all three introduction strategies are shown in Fig. 5.

As can be seen from Fig. 5, the optimality regions of the three introduction approaches depends only on the relative and absolute discounting rates of the firm and the consumer. The following observations can be made from Fig. 5.

(a) When both the firm and the customers are relatively impatient (low and medium values of $\delta_s$ *and* $\delta_c$), but the firm is either more impatient than the customer, or a little more patient ($\delta_s \approx \delta_c$), introducing a product family simultaneously is optimal.

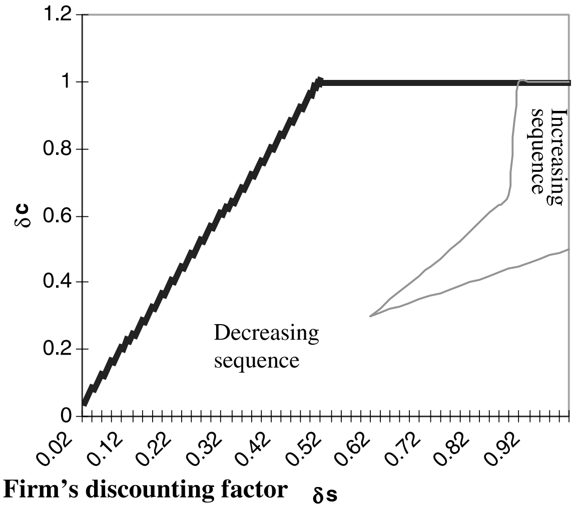


Fig. 4. Discount rates for which sequential upward and downward strategies can exist.

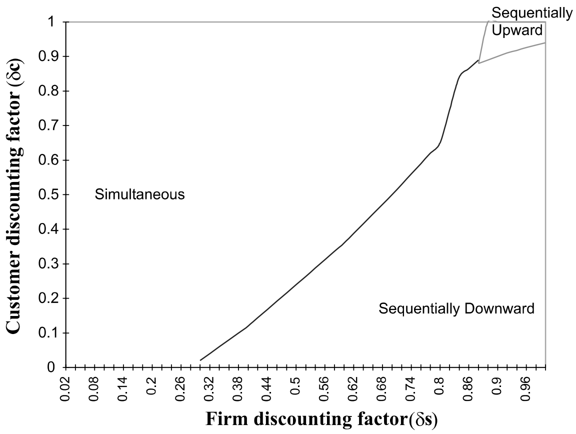


Fig. 5. Optimality of different sequences.

(b) When customers are much more impatient than the firm ($\delta_s \ll \delta_c$), and both the firm and customers are relatively impatient (low and medium values of $\delta_s$ and $\delta_c$), sequentially downward introduction is optimal.

(c) When both the firm and the customers are relatively patient ($\delta_s$, $\delta_c > 0.889$, as described by the shape of the region in Fig. 4), sequentially upward introduction is optimal.

As stated before, the observations are based on a numerical comparison of the profits from the three different launch sequences for different values of $\delta_s$ and $\delta_c$. The appropriateness of the three introduction approaches can be interpreted as follows.

- If consumers are quite willing to wait for the product and the firm is willing to wait for future cash flows, introducing products in an increasing order is optimal. This is because the advancement of cash flows from the low-end product outweighs the reduced profit from the high-end product due to cannibalization.

- If the firm is substantially more patient than consumers, then it should adopt sequentially downward introduction. Since customers are impatient, the profits from the high-end product which is introduced earlier is substantially higher, as the low-end product does not cannibalize the profits from the high-end product. The firm is also more willing to wait for profits to accrue from the low-end product.
- When both the firm and consumers are impatient, but consumers are not significantly more impatient than the firm, then simultaneous introduction is more appropriate. It is superior to sequentially upward introduction as consumers are not willing to wait for the high-end product, and the cannibalization of profits from the high-end product would be high in this case. Sequential downward introduction is also suboptimal because the firm is not willing to wait for the profits from the low-end product. Therefore, introducing the products simultaneously becomes optimal. Our results are different from the existing literature since we show that the sequential upward strategy is optimal when there are constraints on the period in which the high-end product can be offered, hence the firm might find it optimal to introduce the low-end product first, and get immediate profits, even at the expense of a higher degree of cannibalization. Our results complement those of Moorthy and Png (1992), since we show that using continuous distributions, we can model heterogeneity in the market (modeled by the factor "R" in Moorthy and Png, 1992), and based on the distribution of consumer valuations (using Result 1), we can obtain insights into the optimal positioning and segmentation strategy to be used by the firm. The perfectly efficient capital markets case ($\delta_s = \delta_c = \delta$) can be analyzed similarly, so we provide the results.

Simultaneous introduction (same as above):

$$q_1 = \frac{0.2}{c}U, \quad q_2 = \frac{0.4}{c}U, \quad v_1 = 0.6U, \quad v_2 = 0.8U$$

Sequentially upward introduction:

$$q_1 = \frac{6\delta - 4\sqrt{9\delta^2 - 8\delta}}{(64 - 54\delta)c}U, \quad q_2 = \frac{16 - 9\delta - 3\sqrt{9\delta^2 - 8\delta}}{(64 - 54\delta)c}U$$

$$v_1 = \frac{32 - 24\delta - 2\sqrt{9\delta^2 - 8\delta}}{64 - 54\delta}U \quad \text{and} \quad v_2 = \frac{32 - 18\delta - 6\sqrt{9\delta^2 - 8\delta}}{64 - 54\delta}U$$

Sequentially downward introduction:

$$q_1 = \frac{6 - 4\sqrt{9\delta - 8\delta^2}}{(64\delta - 54)c}U, \quad q_2 = \frac{16\delta - 9 - 3\sqrt{9\delta - 8\delta^2}}{(64\delta - 54)c}U$$

$$v_1 = \frac{32\delta - 24 - 2\sqrt{9\delta - 8\delta^2}}{64\delta - 54}U, \quad v_2 = \frac{32\delta - 18 - 6\sqrt{9\delta - 8\delta^2}}{64\delta - 54}U$$

It is interesting to note that in efficient capital markets, with a two-product portfolio, for all the three approaches $v_1 > 0.5$, or more than half the market is not offered a product. This is because serving consumers with lower valuation forces the firm to lower performance quality and consequently, the price and the margin of the lower end product. Therefore, the firm chooses to "skim" the market rather than attempt to gain a larger market share. The domains of optimality in capital markets simplify greatly. In particular, simultaneous introduction is optimal for $\delta < 27/32$, sequentially downward introduction is optimal for $27/32 \leqslant \delta \leqslant 8/9$, and sequentially upward introduction is optimal for $\delta > 8/9$.

*3.2.2. Development sequence and performance with no credible signal possible*

The case where the firm may not be able to provide a credible announcement to the market can be analyzed in a similar fashion. We assume that in this case, consumers do not anticipate the firm's future offerings, and hence, purchase products that give them positive surplus utilities as soon as they are available. Since it may often be the case that consumers may not trust the firm's announcement (the case of vaporware in software industries are an example where the signals sent by firms are not trusted) and buy the products available in the market at that moment to be able to maximize their utilities, the firm has to react accordingly in their product positioning strategy. The following result provides the optimal performance levels, and cutoff valuations when no commitment is possible.

**Result 3**

*Case 1*: Simultaneous introduction (same as above):

$$q_1 = \frac{0.2}{c}U, \quad q_2 = \frac{0.4}{c}U, \quad v_1 = 0.6U, \quad v_2 = 0.8U$$

*Case 2*: Sequentially upward introduction:

$$q_1 = \frac{1}{3c}U, \quad v_1 = \frac{2}{3}U$$

the second product is not offered.

*Case 3*: Sequentially downward introduction:

$$q_1 = \frac{1}{\left(\frac{9}{2} - \frac{2\delta}{3}\right)c}U, \quad q_2 = \frac{1}{\left(3 - \frac{4\delta}{9}\right)c}U \quad v_1 = \frac{1}{\frac{9}{4} - \frac{\delta}{3}}U, \quad v_2 = \frac{1}{\frac{3}{2} - \frac{2\delta}{9}}U$$

- For the case of simultaneous introduction, since both the products are being launched at the same time into the market, the lack of a credible signal (no commitment) does not make a difference, as the customers can self-select the product with the higher surplus. Hence, the performance quality levels are the same as in the previous subsection, this strategy is the same in the cases of credible and non-credible signals (commitment and no-commitment).
- For the case of sequential upward introduction, since customers do not take a signal to be credible, we see that all customers with positive surplus ($vq > p$) buy the low-end product in the first period, hence, the firm will not introduce the high-end product, as the entire market has bought the low-end product. Hence, the firm introduces only one product, which corresponds to the one-product case in Section 2.
- For the case of sequential downward introduction, the firm introduces the high-end product in the second period and the low-end product in the third period. This strategy is viable, since the high-end product is bought by all customers with non-negative surpluses from the product. In the third period, all customers with non-negative surpluses from the low-end product will buy it. Hence, in a market where it is difficult to send a credible signal (no commitment), the simultaneous introduction strategy is the best, followed by the sequentially downward introduction strategy. The sequential upward introduction strategy fails in such a market, as the effect of cannibalization reduces the fraction of the market for the high-end product to zero. It is interesting to note that for all the three introduction strategies, the renewal property of the market can be used gainfully, as the remaining market for the low-end product consists of all consumers whose reservation prices (valuation times performance quality level) is lower than the price of the high-end product as in Besanko and Winston (1990). However, they look at the case of pricing a single product over time to reveal skimming strategies, whereas we study the pricing strategy for two products which are differentiated in performance levels, and introduced sequentially.

We now extend the analysis of this section to two important special cases (i) consumer is offered the option of upgrading to the high-end product, and (ii) the firm faces competition.

### *3.3. The effect of the upgrade option on the strategy of sequential upward introduction*

We begin by analyzing the effect of offering the consumer the option to upgrade from the low-end product introduced in the earlier period to the high-end product in the later period. [4] The option to upgrade to the high-end product in the later period has a significant effect on the firm's product positioning and launch decisions. First, it alleviates consumer anxiety over locking into the low-end product in the earlier period under sequentially upward introduction. Consumers with high valuations can first purchase the low-end product in the earlier period, and then upgrade to the high-end product in the next period. The upgrade option increases the utility to consumers with high valuations, as they now derive utility from the products in both periods. The firm gains from the upgrade option, as the low-end product has a higher demand. In addition to consumers with low valuations who derive a non-negative utility from the low-end product, consumers with high valuations also purchase the product. To capture these effects in our model, we make appropriate changes to the model of upward sequential development that was described in Section 3.1.

#### *3.3.1. Upgrade option with credible signal*

In this section, we assume that the firm can issue a credible signal to the market that a high-end product will be provided later and the consumers can upgrade to the high-end product in the next period. Since the upgrade option provides a suitable mechanism for consumers to avoid the lock-in problem, the market segments are defined somewhat differently from the previous sections. The participation and self-selection constraints must be changed to find the market for the low-end product and the upgrade. Consumers fall in three segments: those selecting only the low-end product only, only the high-end product, or the low-end product in the first period and the upgrade in the next period. This results in somewhat counter-intuitive market segments.

**Result 4**

Offering the upgrade option under sequentially upward introduction creates three market segments (see Fig. 6). Consumers with valuations between $v_1$ and $v_2$ purchase only the low-end product, consumers with valuations from $v_2$ to $v_u$ purchase only the high-end product, while consumers with valuations from $v_u$ to 1 purchase the low-end product in the first period, and upgrade to the high-end product in the subsequent period.

The reasoning for this result is as follows. It is evident that consumers with valuations between $v_1$ and $v_2$ will purchase the low-end product only, as they have low valuations for performance and do not have a positive surplus from purchasing the high-end product. What is interesting is the structure of the other two segments, especially the fact that the people with the highest valuations would choose the upgrade option. Consumers with intermediate valuations (between $v_2$ and $v_U$) have valuations that are high enough to gain the maximum surplus from buying the high-end product in the second period, but their valuations of performance are not high enough to justify purchasing the low-end product in the first period as well. Consumers with the highest valuations per unit of performance quality (between $v_U$ and 1), on the other hand, enjoy the highest surplus from purchasing the low-end product in the first period and upgrading to the high-end product in the second period.

[4] Note that the possibility of upgrading exists only if the firms follows the strategy of upward sequential introduction. If the firm offers both products simultaneously, consumers have access to the high-end product at the same time that they have access to the low-end product. If the firm follows the strategy of downward sequential introduction, the higher-end product is introduced first, so that consumers who buy the lower-end product in the later period do so in spite of having the higher-end product available to them in the second period.

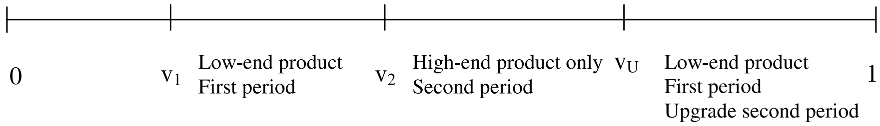


Fig. 6. Market segmentation for sequentially upward introduction with upgrade.

The objective function under the upgrade option will contain profits from the low-end product segment only (from $v_1$ to $v_2$), the high-end product segment only (from $v_2$ to $v_U$), and the upgrade segment (from $v_U$ to 1, who purchase the low-end product in the first period, and the high-end product in the next period). The problem is formally stated as Problem UP.

**Problem UP**

$$\text{Max}\,\Pi = (v_2 - v_1 + 1 - v_U)(p_1 - cq_1^2) + \delta(1 - v_U)\{p_U - (cq_2^2 - cq_1^2 + mq_2 - mq_1)\} + \delta(v_U - v_2) \times (p_2 - cq_2^2)$$

s.t.

$$vq_1 - p_1 = 0 \quad v = v_1 \tag{9}$$

$$vq_1 - p_1 = \delta(vq_2 - p_2) \quad v = v_2 \tag{10}$$

$$(vq_1 - p_1) + \delta\{v(q_2 - q_1) - p_U\} = \delta(vq_2 - p_2) \quad v = v_U \tag{11}$$

$$vq_1 - p_1 \geqslant 0 \quad v_1 \leqslant v < v_2 \tag{12}$$

$$v(q_2 - q_1) - p_U \geqslant 0 \quad v_U \leqslant v < 1 \tag{13}$$

$$vq_2 - p_2 \geqslant 0 \quad v_2 \leqslant v < v_U \tag{14}$$

The first term in the profit maximization formulation represents the profits from the sales of the low-end product, the second term represents the profits from the sale of the upgrade, and the third term represents the profits from the high-end product sales. Here, $p_U$ is the price of the upgrade, the term $cq_2^2 - cq_1^2 + mq_2 - mq_1$ is the unit cost of the upgrade to the firm. The term $cq_2^2 - cq_1^2$ models the difference in unit costs between the two products, and the term $mq_2 - mq_1$ models the additional cost of upgrading. Eqs. (9)–(11) state the conditions for marginal consumers at $v_1$, $v_2$ and $v_U$. Eq. (9) states that the consumer with a valuation of $v_1$ is indifferent between not buying at all and buying only the low-end product. Eq. (10) ensures that the consumer with a valuation of $v_2$ is indifferent between buying only the low-end product and only the high-end product. Eq. (11) ensures likewise that the consumer with a valuation of $v_U$ is indifferent between buying only the high-end product, and resorting to the upgrade option. Constraints 12–14 are the participation constraints for the consumers in these three segments.

**Proposition 1.** *If the discounting rate is high, then more customers prefer to upgrade rather than purchase the high-end product only in the second period. If the discounting rate is low, then more customers prefer to buy the high-end product only in the second period. The profits from the upgrade option always dominate the profits without the upgrade option.*

It is intuitive that if the firm can offer an upgrade, consumers are not wary of getting locked into the lower-end product. A larger number of consumers are willing to purchase the lower-end product, as they can enjoy the benefits of the high-end product too by upgrading later. The margin of the upgrade is lower than the margin of the high-end product in the no-upgrade case, but this is more than compensated for by the higher sales volume of the low-end product to the upgrading consumers resulting in higher profit. *It is* *also interesting to note that the firm will introduce an upgrade even if $\delta$ is very low.* [5] *In this case, the market for the high-end product only* ($v_2$ *to* $v_U$) *is higher. The value of* $q_1$ *and* $v_1$ *is lower here than in the no-upgrade case to reduce the unit variable cost of the low-end product. Since* $v_1$ *is lower, the total market coverage is higher because of the upgrade option. The value of* $q_2$ *is lower so that a significant fraction of consumers who purchased the low-end product can upgrade to the high-end product. As expected, the total market for the high-end product* (*i.e., those who purchase the high-end product only, and those who upgrade to the high-end product*) *is higher than the no-upgrade case.* The profits when the firm offers the upgrade option always dominates the profits for the three previous cases, because of the higher market volume and low-discounting associated with the low-end product. The advantage of offering the upgrade option is thus a higher market share, and an early accrual of profits from the low-end product.

*3.3.2. Upgrade case with no credible signal possible*

If the market will not accept any signal from the firm about committing to an upgrade later, we see that introducing an upgrade is still profitable. If the firm introduces a low-end product in the first period, then all customers with non-negative surpluses will buy the low-end product in the first period itself, and will not postpone their purchase for a better product in the second period. Hence, we will only have two classes of customers: those who buy the low-end product in the first period, and those who upgrade to the high-end product in the second period.

**Proposition 2.** *If the firm cannot make a credible announcement about the launch of an upgrade, the sequential upward strategy is still optimal, and dominates the sequential downward and simultaneous introduction strategies with no commitment.*

The proof of the proposition is in the appendix, we present the intuition here. Since there cannot be a credible signal issued by the firm, all customers with a non-negative surplus will purchase the low-end product. However, that increases the profits of the firm compared to the previous case with commitment, as it can extract out all the surpluses from the consumers, the consumers suffer the effects of the lack of a credible commitment in this case. This shows that in the absence of a credible commitment by the firm, the upgrading option is the best option available to the firm. As seen in both Sections 3.3.1 and 3.3.2, the sequential upward strategy with the upgrade option always dominates the simultaneous introduction strategy and the strategy of sequential downward introduction. The upgrade option gives flexibility in choice to both the firm and the consumers. The upgrade option provides the firm a less costly way of making new products, as the entire product does not have to be introduced again, however, the firm can extract a higher fraction of the surplus from providing a higher performance level to the consumer. Similarly, *t* provides the consumer with the flexibility of being able to enjoy the higher utility from the high-end product when it is released later, and the early utility from the low-end product, which the consumer prefers if s/he is impatient. Garud and Kumaraswamy (1993) provide a framework which shows that by adopting open systems, most firms in the technology markets take advantage of the upgrade option by providing consumers with a series of products, which have a high degree of commonality, and hence can be upgraded. This enables the firm to get a higher market share, as demonstrated in this paper, and additionally, makes the firm more capable of rapid innovation. We now analyze the impact of competition on the choice of introduction sequence of the firm.

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[5] If $\delta$ is very low, most of the consumers will purchase only the low-end product, but there will be a few high-end consumers who still adopt the upgrade since it gives them more utility. As $\delta$ tends to zero, the value of $v_1$ tends to 0.666, the optimal *v* for a single product.

### 3.4. *Impact of competition on product family development planning: Two-product case*

In this section, we analyze the impact of a competitive environment on the positioning, segmentation, and introduction sequence of two products. We analyze a duopolistic scenario using a game-theoretic framework, in which two firms commit to develop each of the two differentiated products. First, we analyze the case where the firm can issue a credible announcement in Section 3.4.1, followed by the case where a credible signal cannot be issued in Section 3.4.2.

#### 3.4.1. *Product positioning and market segmentation under competition when a credible signal can be issued*

In this section, we conduct a game-theoretic analysis of a duopoly situation and derive insights into the positioning, introduction sequence and market segmentation strategies of two firms that introduce one of the two products. The two firms (labeled 1 and 2) choose their respective price and performance levels to determine their relative positions in the market. The results obtained are compared to the base case, which is the monopolist with the corresponding two-product introduction strategy.

Without loss of generality, suppose firm 1 commits to developing the low-end product, and firm 2 commits to developing the high-end product. Let firm *i*s product be offered at a performance quality of $q_i$ and a price of $p_i$. The objectives of the two firms, to maximize their own profit from their respective products, is as follows:

$$\text{Firm}\,1 - \text{Max}\Pi_1 = \gamma(v_2 - v_1)(p_1 - cq_1^2), \quad \text{Firm}\,2 - \text{Max}\Pi_2 = \mu(1 - v_2)(p_2 - cq_2^2).$$

For ease of analysis, we again assume a perfectly efficient capital market, i.e., the customers and the firm have the same discounting rate, $\delta$, $\gamma$ and $\mu$ are the discounting factors for the different sequences, e.g. for the simultaneous introduction case, $\gamma = \mu = \delta$, and for the sequential upward introduction case, $\gamma = 1$, $\mu = \delta$. The self-selection and participation constraints are the same as those in the simultaneous introduction model. Specifically, the marginal consumers will have valuations of $v_1$ and $v_2$ such that $p_1 = v_1 q_1$ and $p_2 = v_2 q_2 - (\gamma/\mu)(v_2 - v_1)q_1$. To find the Nash equilibrium in prices for the two firms in this non-cooperative game, we solve the equations $(\partial\Pi_i/\partial p_i) = 0$, $i = 1, 2$; simultaneously for both firms. The optimal prices are presented in Result 4 in the appendix. The Nash equilibrium prices are substituted back into $\Pi_1$ and $\Pi_2$ to obtain the optimal performance levels of the two products. The effect of competition on the introduction sequence, prices, performance levels, and the respective market segment sizes of the low-end and high-end products are discussed in the proposition below.

**Proposition 3.** *In the presence of competition, for all three introduction sequences, the optimal price of the low-end product decreases* (*relative to the monopolist case*), *while the optimal price of the high-end product increases. The market share of the low-end product is higher, while the market share of the high-end product decreases slightly. The firm producing the low-end product has the highest profits from the sequential upward introduction case* (*when it introduces the product in the first period and the other firm introduces the high-end product in the next period*).

For the simultaneous introduction case, the optimal prices, performance levels, and marginal consumer valuations are given by

$$p_1 = \frac{0.109}{c}, \quad q_1 = \frac{0.2473}{c}, \quad v_1 = 0.4404, \quad \Pi_1 = \frac{0.0173}{c}$$

and

$$p_2 = \frac{0.335}{c}, \quad q_2 = \frac{0.528}{c}, \quad v_2 = 0.8032, \quad \Pi_2 = \frac{0.0109}{c}.$$

The proposition is proved in the Appendix, the intuition is presented here. As expected, the optimal performance levels are higher for both products in the competitive case, which corroborates the existing theory. Also, the price of the low-end product is lower, because even though the unit cost of production has increased, competition forces firm 1 to charge a lower price. In doing so, firm 1 gains a larger market share, as a larger fraction of consumers in the market can now purchase the low-end product (as the surplus is positive for consumers with lower valuations. The total sales from both products put together increases under competition. Therefore, firm 1 competes on the basis of volume, i.e., it has a lower margin, but a market share of nearly 36% (compared to the 20% share in the corresponding monopolistic case) compensating for the lower margin.

The performance level of the high-end product has to be significantly increased under competition, to distinguish itself from the low-end product. This increases the unit variable cost of the high-end product (as the unit cost is of the form $cq^2$). The price charged has to be higher to compensate for this disproportionate increase in the unit variable cost. Since both the performance and price increase, firm 2 has about the same market share as in the monopolistic case. Surprisingly, the profits attained by firm 1 are higher than the profits attained by firm 2, unlike in the monopolistic case, where the high-end product has a greater contribution to the profits than the low-end product. The high-end product has to be substantially differentiated (has a higher unit variable cost), and hence has a low margin, while the volume for the product stays almost the same. This causes the decrease in profits. This effect is strengthened when the low-end product is introduced in the first period and the high-end product is introduced in the next period. Some impatient customers who would have bought the high-end product if it were available will now buy the low-end product as they derive higher discounted utility from the low-end product. The low-end product will never be introduced after the high-end product if firm 1 has the technology available, as the profits from sequential downward introduction are the lowest for firm 1 of the three introduction sequence cases. This reinforces the intuition that in a competitive environment, a firm that has the low-end product introduces it first to preempt the other player.

*3.4.2. Product positioning and market segmentation with no credible signal in competition*

If the firm cannot issue a credible signal about introducing a product in the future in the market, then only the simultaneous introduction and sequentially downward strategies can exist in equilibrium. To see why, note that if the low-end product is introduced in the market first, then no one will buy the high-end product later, as customers just buy one product, since they do not believe that there will be a better product later, customers will choose to adopt the low-end product when it is available. If the products are introduced simultaneously by the two competitors, then the results from the previous section will still hold, since the customers can self-select the product of their own choice immediately. For the sequential downward introduction case, firm 2 introduces the high-end product in period 2, followed by the introduction of the low-end product in period 3.

**Proposition 4.** *If the firms cannot issue a credible signal to the customers about the time of introduction of their products, then the results of Proposition 3 hold for the strategy of both firms introducing the products simultaneously. If the low-end product is introduced first, then the second firm will not introduce the high-end product later. If the high-end product is introduced first, it captures a higher fraction of the market than the case with a credible signal. The low-end product is introduced later, and captures a lower fraction of the market than the case with a credible signal.*

The above results show that with no credible signal possible, firm 1 will try and introduce its product as soon as possible, as it benefits from locking out the competition by introducing the product first. This reinforces the results in the previous section, viz., by introducing a low-end product early in the market, the firm can obtain higher profits, as all customers adopt the low-end product immediately. If firm 1 does not have the technological capabilities that firm 2 has, then it is possible that firm 2 introduces the high-end product first, by which it gains market share compared to the low-end product. Even though the profits for firm 2 are higher in this strategy, firm 1 can still have positive profits, as some consumers will wait and adopt the low-end product since the price of the low-end product is lower.

We now present a conceptual framework for introduction sequence decision-making from the model insights.

## 4. A conceptual framework for the model insights

The model presented in the previous sections helps derive analytical expressions for product positioning, market segmentation, and profit from each introduction sequence for a firm experiencing concurrent development of core technology. In this section, we translate the model findings into a conceptual framework that presents managerial insights. Fig. 7 presents the regions of appropriateness of each of the different introduction sequences.

Moorthy and Png (1992) showed that in the absence of exogenous technological improvement, simultaneous and downward sequential introduction dominate the upward sequential introduction approach. *Our major contribution is to show that upward sequential introduction can be optimal in a variety of circumstances when the operational issues of concurrent product and technology development are modeled.* In particular, if the firm can make a credible announcement about the relative performance of the products and when both the firm and the consumer have about the same discount factors and are both more patient, the upward sequential introduction approach dominates simultaneous and downward sequential introduction approaches. Part of the reason is the early accrual of profits from the low-end product. More importantly, following the upward sequential strategy enables the firm to deliver the best possible product when it is available, resulting in higher margins for the high-end product.

When the firm and consumers become more impatient, *simultaneous* and downward sequential introduction approaches become more viable. These strategies are also better when the firm cannot make a credible commitment about the relative performances of the products, as the high-end product will not be adopted if the firm adopts the upward sequential strategy. In particular, when the firm and the consumers discount benefits rapidly, the *simultaneous introduction* strategy is the most effective. The downward sequential introduction approach is optimal for medium values of discounting, as it enables the firm to post greater profits on the high-end product. Consumers are willing to wait to some extent for the low-end product in the later period. Clearly, the cost of cannibalization is also the lowest in this case (Moorthy and Png, 1992), so, a high degree of cannibalization favors the *downward sequential* strategy.

| Factor | Upward Sequential Introduction | Simultaneous Introduction | Downward Sequential Introduction |
|---|---|---|---|
| *Discounting Factor of Firm and Customer* | Appropriate when firm and consumer discounting factor is high | Appropriate when firm and consumer discounting factor is low, and consumer is more patient than firm | Appropriate when firm and consumer discounting factor is low, and firm is more patient than consumer |
| *Design for Upgrade* | More attractive with the possibility of upgrade | Less attractive with the possibility of upgrade | Less attractive with the possibility of upgrade |
| *Cannibalization* | Appropriate when cannibalization is low | Appropriate for medium cannibalization | Appropriate when cannibalization is high |
| *No credible signal possible* | Attractive option to lock out the market | Attractive option for firm with low-end product | Attractive for firm with superior capability |

Fig. 7. Comparison of different introduction approaches.

| Variable | Low-end product | High-end product |
| --- | --- | --- |
| *Performance Quality* | Increases | Increases |
| *Price* | Price decreases slightly | Price increases significantly |
| *Market share* | Market share increases significantly | Market share decreases slightly |
| *Profit* | Increases significantly | Decreases signficantly |

Fig. 8. Effect of competition on the low and high-end products.

When the firm offers consumers the option of upgrading to the high-end product at the end of the second period, the *upward sequential* strategy becomes optimal in a larger number of situations. The option of upgrading to the high-end product offers an incentive to consumers with very high valuations to purchase the low-end product and purchase the upgrade when it becomes available. When the firm can issue a credible commitment about the relative performances of products, the firm gets a higher market share for the low-end product, as the price of the low-end product is reduced, and in the second period, gets a significant market share for the upgrade. The upgrade option also enables the firm to reduce the cost of cannibalization of sales in the *upward sequential* approach, making it more attractive. When the firm cannot issue a credible signal, the *upward sequential* approach with the upgrade option is still more attractive, as all consumers adopt the low-end product, and the firm does not have to reduce the price of the low-end product significantly. The upgrade high-end product is then purchased when it is available, and since the quality of the upgrade is higher, the firm can extract a higher margin. Surprisingly, in this case, the lack of a credible signal helps the firm extract the maximum surplus from the consumers.

The game-theoretic model of competition helps understand the effect of competition on product performance levels and prices. A summary of the findings is presented in Fig. 8. When the competing firms can issue a credible signal, we find that the firm developing the low-end product must increase its performance quality and decrease its price slightly compared to the monopoly case where both products are developed by the same firm. In the Nash equilibrium, the high-end product has to differentiate itself significantly in terms of performance and price from the low-end product. Therefore, the competitive environment affects the firm with the high-end product much more significantly than the firm with the low-end product.

Since the performance of the low-end product is substantially higher, and its price only slightly higher, it enables more consumers with lower valuations to purchase the product. This gives the low-end product a substantial increase in its market share at the cost of a small decrease in margin. The profit of the low-end product is therefore higher than the corresponding monopoly case. The margin of the high-end product is substantially lower than in the monopoly case, and the market share decreases marginally. The profit from the high-end product in a competitive environment is, therefore, lower than that of the low-end product. This effect is stronger when the low-end product is introduced before the high-end product, as the cannibalization of the high-end product is even higher due to delayed launch.

When the competing firms cannot issue a credible signal, we find that both the firm developing the low-end product will try to introduce it into the market as quickly as possible, so as to lock out the competition from the market. All consumers will buy the low-end product, as they do not believe there will be better products available later. When one firm has a superior technological capability, they may be able to introduce a high-end product and get a substantial profit from it, if the other firm cannot introduce a product early. In this case, the firm with the low-end product can still introduce it later after the launch of the high-end product, in this case, the low-end product has much lower profits.

The above observations can be illustrated with the product development effort at a Fortune 100 telecommunications company ("study company"). The development team that we interacted with at the study company designs network testing sets that detect physical faults in telecom networks. Prior to telecom deregulation in the United States, the study company worked with customers who had a virtual monopoly. The pace of technological advancements was relatively slow, the firm and its customers were historically more interested in minimizing cannibalization, they launched products in a decreasing order of performance. Due to intensifying competition caused by telecom industry de-regulation and the rapid development of core technologies such as digital signal processors, the effects of technological advancements must now be balanced with that of de-regulation.

We raised this issue with the team leader asking him if the downward sequential approach (of launching products in a decreasing order of performance) was still appropriate for the company's new business environment. In our discussion, we learned that the increasing component of software and the use of electronic circuits called field programmable gate arrays in the network testing kits made them more easily upgradeable on the field and more appealing to customers with potential (but not immediate) high-end uses. Also, we pointed out to the study company that intensifying competition and the emphasis on shareholder value creation made the discounting factor of both the firm and its customers high. Further, as shown in Fig. 6, in a competitive environment greater share of profits accrue from the low-end product and if a competitor were to pre-empt the study company by introducing the low-end product, that would significantly cut into its life-cycle profits. All the above factors argued for not delaying the introduction of low-end products until the high-end product is launched. Using our insight model, we showed the team leader how the firm could sustain its leadership if it introduced products in an increasing order of performance and minimized cannibalization by offering customers an upgrade path. The team leader pointed out that the threat of cannibalization can be further managed/reduced through external differentiation in form (using cheaper materials for housing etc.), and has expressed interest in adopting a upward sequential approach for their forthcoming product launches.

We now present our conclusions from the study, and avenues for future research.

## 5. Discussions and conclusions

Our analysis in this paper indicates that in the presence of exogenous technological improvements, launching products in an increasing order of performance can be not only profitable but also even optimal for a range of circumstances. In addition, if the firm offers its consumers the option of upgrading to a high-end product in a subsequent period, then the cost of cannibalization can be reduced and introducing products in an increasing order of performance becomes even more appropriate. These findings add a new dimension to the literature on positioning and introduction sequence of technology-based products.

In developing the model, we made several modeling assumptions, and we review the major assumptions here. For instance, we have used a linear utility model to quantify customer surplus from a product, an assumption that has also been used in the literature before (Mussa and Rosen, 1978; Spence, 1980). When this assumption does not hold and the utility is a concave or convex function of the surplus, we can use sensitivity analysis to determine the impact of the linearity assumption on the results of our model. It was also assumed that the unit variable cost exhibits constant returns to scale and is a squared function of the performance of the product. The quadratic form is only used to derive expressions for the optimal performance levels and market segments, and the analysis of the model reveals similar insights for other convex cost functions. We propose to investigate in future research the implication of scale and scope economies in the cost function. Also, this paper does not include a term for development costs, but it may be seen qualitatively that the effect of a development cost term would be to reduce the gap between the performance levels of succeeding products, thus increasing the cost of cannibalization.

Our modeling and analysis of the product positioning and introduction sequence decisions has several implications for product development practice. First, the need to develop products concurrently with the underlying technology creates the setting where product positioning decisions must be made amidst exogenous technology improvements. Under these conditions, introducing products as and when they are available is an attractive approach when the cost of cannibalization is low or when the firm can offer the customer the option to upgrade to a higher performance product. Recent observations in the software industry offer evidence that other firms too might be using this approach to their advantage. For instance, in the web-browser market, Microsoft and Netscape have increasingly resorted to the sequential upward approach to introducing their new products. In closing, this paper makes a contribution to the product development literature by drawing attention to the interactions between the product being developed and its underlying technology. We also address the challenges facing the firm in making product positioning and introduction sequence decisions amidst improvements in such core technology.

## Appendix A

### *A.1. Proof of Result 3*

The proof follows from a numerical ordering of the surplus in utilities associated with specific options. If a customer purchases the low-end product only, the surplus utility is given by

$$U(\text{Low-end product}) = vq_1 - p_1 = q_1 v - p_1.$$

For customers who purchase the high-end product only,

$$U(\text{High-end product}) = \delta(vq_2 - p_2) = \delta q_2 v - \delta p_2.$$

For customers who purchase the low-end product and then the upgrade to the high-end product,

$$\begin{aligned} U(\text{Low-end product} + \text{Upgrade}) &= vq_1 - p_1 + (1-\delta)[v(q_2 - q_1) - p_U] \\ &= [(1-\delta)q_1 + \delta q_2]v - p_1 - p_U \end{aligned}$$

From the above three surplus utility equations, we see that customers with higher valuations (Higher values of $v$) derive greater surplus from the high-end product only compared to the low-end product only, and from the (low-end product + upgrade option compared to the high-end product only. Therefore, the ordering in Result 3 holds true. □

### *A.2. Proof of Result 1*

We present the proof here for the case of simultaneous introduction of the products ($\gamma = \mu$). For the other two cases, the proof is analogous. To find the optimal values of $q_1$ and $q_2$, we substitute the optimal prices back into the profit function to obtain the following expression for the profit:

$$\Pi = [F(v_2) - F(v_1)][v_1 q_1 - cq_1^2] + [1 - F(v_2)][v_2 q_2 - (v_2 - v_1)q_1 - cq_2^2]$$

This expression can be rearranged as follows to obtain the optimal values of $q_1$ and $q_2$.

$$\Pi = [F(v_2) - F(v_1)]\left[v_1 q_1 - (v_2 - v_1)q_1 \frac{1 - F(v_2)}{F(v_2) - F(v_1)} - cq_1^2\right] + [1 - F(v_2)][v_2 q_2 - cq_2^2]$$

The first-order conditions give us the optimal values of quality for the low-end and high-end product respectively.

$$q_1 = \frac{1}{2c}\left[v_1 - (v_2 - v_1)\frac{1-F(v_2)}{F(v_2)-F(v_1)}\right] \quad \text{and} \quad q_1 = \frac{v_2}{2c}.$$

Substituting the optimal qualities back into the expression for profits, we obtain the following expression for the profits, which are only in terms of $v_1$ and $v_2$.

$$\Pi = \frac{[F(v_2)-F(v_1)]}{4c}\left[v_1 - (v_2 - v_1)\frac{1-F(v_2)}{F(v_2)-F(v_1)}\right]^2 + \frac{[1-F(v_2)]}{4c}v_2^2 \tag{A.1}$$

Since the marginal valuations $v_i$ and the prices $p_i$ are related in a linear fashion, $\Pi$ can be equivalently optimized in terms of $q$ and $v$, rather than for $p$ and $v$, this has the added benefit of simplifying the analysis. The first-order condition for $v_1$ gives us

$$\frac{\partial \Pi}{\partial v_1} = 0 \Rightarrow [F(v_2)-F(v_1)]2\left[1 - \frac{-\{F(v_2)-F(v_1)\}\{1-F(v_2)\} + (v_2 - v_1)f(v_1)}{\{F(v_2)-F(v_1)\}^2}\right]$$
$$= f(v_1)\left[v_1 - (v_2 - v_1)\frac{1-F(v_2)}{F(v_2)-F(v_1)}\right]$$

This can be further simplified to:

$$2[F(v_2)-F(v_1)] + 2[1-F(v_2)] - 2(v_2 - v_1)f(v_1)\frac{1-F(v_2)}{F(v_2)-F(v_1)}$$
$$= v_1 f(v_1) - (v_2 - v_1)f(v_1)\frac{1-F(v_2)}{F(v_2)-F(v_1)}$$

or

$$2[1-F(v_1)] = v_1 f(v_1) + (v_2 - v_1)f(v_1)\frac{1-F(v_2)}{F(v_2)-F(v_1)},$$

which reduces to:

$$\frac{2}{r_1} = v_1 + (v_2 - v_1)\frac{1-F(v_2)}{F(v_2)-F(v_1)} \tag{A.2}$$

Before applying the first order condition for $v_2$, transform Eq. (A.1) in the following manner.

$$\Pi = \frac{[F(v_2)-F(v_1)]}{4c}\left[v_1 - (v_2 - v_1)\frac{1-F(v_2)}{F(v_2)-F(v_1)}\right]^2 + \frac{[1-F(v_2)]}{4c}v_2^2 \tag{A.1}$$

$$4c\Pi = v_1^2[F(v_2)-F(v_1)] - 2v_1(v_2 - v_1)[1-F(v_2)] + (v_2 - v_1)^2\frac{[1-F(v_2)]^2}{F(v_2)-F(v_1)} + [1-F(v_2)]v_2^2$$

or

$$4c\Pi = v_1^2[F(v_2)-F(v_1)] + (v_2^2 - 2v_1v_2 + 2v_1^2)[1-F(v_2)] + (v_2 - v_1)^2\frac{[1-F(v_2)]^2}{F(v_2)-F(v_1)}$$

or

$$4c\Pi = v_1^2[1-F(v_1)] + (v_2 - v_1)^2[1-F(v_2)]\left[1 + \frac{1-F(v_2)}{F(v_2)-F(v_1)}\right]$$

or

$$4c\Pi = v_1^2[1 - F(v_1)] + (v_2 - v_1)^2[1 - F(v_1)]\left[\frac{1 - F(v_2)}{F(v_2) - F(v_1)}\right]$$

The first-order condition for this transformed expression with respect to $v_2$ gives us

$$\frac{\partial \Pi}{\partial v_2} = 0 \Rightarrow [F(v_2) - F(v_1)][2(v_2 - v_1)\{1 - F(v_2)\} - (v_2 - v_1)^2 f(v_2)] = (v_2 - v_1)^2[1 - F(v_2)]f(v_2)$$

or

$$2[F(v_2) - F(v_1)][1 - F(v_2)] = (v_2 - v_1)f(v_2)[1 - F(v_1)]$$

The above expression reduces to

$$\frac{2}{r_2} = (v_2 - v_1)\frac{1 - F(v_1)}{F(v_2) - F(v_1)} \tag{A.3}$$

Solving Eqs. (A.2) and (A.3) simultaneously gives us the result in Result 1. □

*A.3. Proof of Result 2*

We present the proof of the results in the simultaneous introduction case. The sequential upward and sequential downward introduction cases follow analogously. The conditions for the utility of marginal consumers gives $p_1 = v_1 q_1$, and $p_2 = v_2 q_2 - (v_2 - v_1)q_1$. Using these prices in the profit function, we obtain $v_1 = (p_1/q_1)$ and $v_2 = (p_2 - p_1)/(q_2 - q_1)$. Substituting these values into the profit function, we get

$$\Pi = \left[\frac{p_2 - p_1}{q_2 - q_1} - \frac{p_1}{q_1}\right](p_1 - cq_1^2) + \left[1 - \frac{p_2 - p_1}{q_2 - q_1}\right](p_2 - cq_2^2)$$

The first order conditions with respect to $p_1$ and $p_2$ gives us

$$\frac{\partial \Pi}{\partial p_1} = 0 \Rightarrow \left[\frac{-1}{q_2 - q_1} - \frac{1}{q_1}\right](p_1 - cq_1^2) + \left[\frac{p_2 - p_1}{q_2 - q_1} - \frac{p_1}{q_1}\right] + \frac{p_2 - cq_2^2}{q_2 - q_1} = 0$$

which simplifies to

$$\frac{2p_2 - 2p_1 - cq_2^2 + cq_1^2}{q_2 - q_1} = \frac{2p_1 - cq_1^2}{q_1} \tag{A.4}$$

$$\frac{\partial \Pi}{\partial p_2} = 0 \Rightarrow \frac{p_1 - cq_1^2}{q_2 - q_1} - \frac{p_2 - cq_2^2}{q_2 - q_1} + 1 - \frac{p_2 - p_1}{q_2 - q_1} = 0$$

which simplifies to

$$\frac{2p_2 - 2p_1 - cq_2^2 + cq_1^2}{q_2 - q_1} = 1 \tag{A.5}$$

From Eqs. (A.4) and (A.5), we find $p_1 = (cq_1^2 + q_1)/2$ and $p_2 = (cq_2^2 + q_2)/2$. Substituting these optimal prices back into the profit function, we get

$$\Pi = \frac{cq_2}{2}\left[\frac{q_1 - cq_1^2}{2}\right] + \frac{1}{2}[1 - c(q_1 + q_2)]\left[\frac{q_2 - cq_2^2}{2}\right]$$

The first-order condition for $q_1$ gives us

$$\frac{\partial \Pi}{\partial q_1} = 0 \Rightarrow cq_2[1 - 2cq_1] - c(q_2 - cq_2^2) = 0 \quad \text{or} \quad q_2 = 2q_1$$

The first-order condition for $q_2$ gives us

$$\frac{\partial \Pi}{\partial q_2} = 0 \Rightarrow c(q_1 - cq_1^2) - c(q_2 - cq_2^2) + [1 - c(q_1 + q_2)[1 - 2cq_2] = 0$$

or $3cq_2 = 1 + cq_1$ or $q_1 = 0.2/c$ and $q_1 = 0.4/c$. The other parts of Result 2 follow. □

*A.4. Proof of Proposition 1*

We begin by showing that constraints 12–14 are redundant because they are satisfied if constraints 9–11 are satisfied. From constraint 9, $v_1 q_1 = p_1$. It follows that 12 is trivially satisfied, because $vq_1$-$p_1$ is greater than zero if v is greater than $v_1$. From constraint 10, $v_2 q_2 - p_2 = (1/\delta)(v_2 q_1 - p_1) = (1/\delta)(v_2 - v_1)q_1 > 0$. It follows that if $v$ is greater than $v_2$, then constraint 14 is satisfied. Similarly, given the linear ordering $v_U > v_2$, 13 is satisfied if 11 is satisfied.

We solve for the optimal values of $p_1$, $p_2$, $v_1$, $v_2$, $q_1$, and $q_2$ here in a similar fashion to the cases before by solving for the prices using the utilities of the marginal consumers. Solving Eqs. (9)–(11) gives us

$$v_1 = \frac{p_1}{q_1}, \quad v_2 = \frac{\delta p_2 - p_1}{\delta q_2 - q_1}, \quad v_U = \frac{p_1 + \delta p_U - \delta p_2}{q_1(1-\delta)}$$

Substituting the values of $v_1$, $v_2$ and $v_U$ in the profit function, $\Pi$ can be rewritten as:

$$\Pi = \left[\frac{\delta p_2 - p_1}{\delta q_2 - q_1} - \frac{p_1}{q_1}\right](p_1 - cq_1^2) + \delta\left[\frac{p_1 + \delta p_U - \delta p_2}{q_1(1-\delta)} - \frac{\delta p_2 - p_1}{\delta q_2 - q_1}\right](p_2 - cq_2^2) + \left[1 - \frac{p_1 + \delta p_U - \delta p_2}{q_1(1-\delta)}\right][p_1 - cq_1^2 + \delta\{p_U - (cq_2^2 - cq_1^2 + mq_2 - mq_1)\}]$$

Applying the first-order conditions for $p_1$, $p_2$, and $p_U$, we get:

$$\frac{\partial \Pi}{\partial p_1} = 0 \Rightarrow \left[\frac{-1}{\delta q_2 - q_1} - \frac{1}{q_1}\right](p_1 - cq_1^2) + \frac{\delta p_2 - p_1}{\delta q_2 - q_1} - \frac{p_1}{q_1} + \delta\left[\frac{1}{q_1(1-\delta)} + \frac{1}{\delta q_2 - q_1}\right](p_2 - cq_2^2) + 1 - \frac{p_1 + \delta p_U - \delta p_2}{q_1(1-\delta)} - \frac{1}{q_1(1-\delta)}[p_1 - cq_1^2 + \delta\{p_U - (cq_2^2 - cq_1^2 + mq_2 - mq_1)\}] = 0$$

This reduces to the condition:

$$\frac{-2p_1 + 2\delta p_2 + cq_1^2 - \delta cq_2^2}{\delta q_2 - q_1} + \frac{-2p_1 + cq_1^2}{q_1} + 1 + \frac{1}{q_1(1-\delta)} \times [-2p_1 + 2\delta p_2 - 2\delta p_U + cq_1^2(1-\delta) + \delta(mq_2 - mq_1)] = 0 \quad \text{(A.6)}$$

$$\frac{\partial \Pi}{\partial p_2} = 0$$

$$\Rightarrow \frac{1}{\delta q_2 - q_1}(p_1 - cq_1^2) + \delta\left[\frac{-1}{q_1(1-\delta)} + \frac{-1}{\delta q_2 - q_1}\right](p_2 - cq_2^2) + \frac{p_1 + \delta p_U - \delta p_2}{q_1(1-\delta)} - \frac{\delta p_2 - p_1}{\delta q_2 - q_1}$$
$$+ \frac{1}{q_1(1-\delta)}[p_1 - cq_1^2 + \delta\{p_U - (cq_2^2 - cq_1^2 + mq_2 - mq_1)\}]$$
$$= 0$$

This reduces to the condition:

$$\frac{2p_1 - 2\delta p_2 - cq_1^2 + \delta cq_2^2}{\delta q_2 - q_1} + \frac{1}{q_1(1-\delta)}[2p_1 - 2\delta p_2 + 2\delta p_U - cq_1^2(1-\delta) - \delta(mq_2 - mq_1)] = 0 \quad \text{(A.7)}$$

$$\frac{\partial \Pi}{\partial p_U} = 0 \Rightarrow \frac{\delta}{q_1(1-\delta)}(p_2 - cq_2^2) + 1 - \frac{p_1 + \delta p_U - \delta p_2}{q_1(1-\delta)} - \frac{p_1 - cq_1^2 + \delta\{p_U - (cq_2^2 - cq_1^2 + mq_2 - mq_1)\}}{q_1(1-\delta)}$$
$$= 0$$

This reduces to the condition:

$$-2p_1 - 2\delta p_U + 2\delta p_2 = (q_1 + cq_1^2)(1-\delta) + \delta(mq_2 - mq_1) \quad \text{(A.8)}$$

Substituting this result in (A.7), we get

$$2p_1 - cq_1^2 - 2\delta p_2 + \delta cq_2^2 = -\delta q_2 - q_1$$

Substituting this result back in (A.6), we get

$$p_1 = \frac{cq_1^2 + q_1}{2}, \quad p_2 = \frac{cq_2^2 + q_2}{2}, \quad p_U = \frac{1}{2}(1+m)(q_2 - q_1) + \frac{cq_2^2 - cq_1^2}{2}$$

and 14 are the participation constraints for the consumers in these three segments.

The optimal values of $v_1$, $v_2$ and $v_U$ are given by

$$v_1 = \frac{1 + cq_1}{2}, \quad v_2 = \frac{1}{2} + \frac{\delta cq_2^2 - cq_1^2}{2(\delta q_2 - q_1)}, \quad v_U = \frac{1}{2} + \frac{cq_1}{2} + \frac{\delta m(q_2 - q_1)}{2q_1(1-\delta)}$$

The other parts of the result follow from here. These optimal prices are substituted back into the profit function to derive implicit equations for $q_1$ and $q_2$, which are then solved numerically for different values of $\delta$.

**Proof of Proposition 2**: Since consumers do not apply any foresight, all consumers who have a valuation higher than $v_1$ will purchase the low-end product in the first period. In the second period, those consumers who upgrade will do so iff $v_2 q_2 - p_U \geqslant v_2 q_1$, i.e., they obtain a higher utility from the upgrade than the price they pay for the upgrade. The firm will therefore, price the upgrade to make the above constraint hold at equality, i.e., $p_U = v_2(q_2 - q_1)$. Since the cost of the upgrade is $c(q_2 - q_1)^2$, in the second period, the firm optimizes $\Pi_2 = (1 - v_2)[p_U - c(q_2 - q_1)^2]$. Substituting the value of the price into the profit function, we see that the cutoff valuation $v_2$ is given by $q_2 = (v_2/2c) + q_1$. Substituting back, we get $\Pi_2 = (1 - v_2)(v_2^2/4c)$. In the first period, the firm optimizes the following program:

$$\begin{aligned} &\text{Max}\,\Pi = (1 - v_1)(p_1 - cq_1^2) + \delta\Pi_2 \\ &\text{s.t.} \quad v_1 q_1 - p_1 \geqslant 0 \\ &\qquad\;\; v_1 \leqslant v_2 \end{aligned}$$

Firm 1 sets $p_1 = v_1 q_1$, and optimizes the profits from the two periods. Since the profits from the two periods are temporally independent except for the constraint on $v_1$, the two problems can be solved independently, getting $v_1 = v_2 = 0.67$. Hence, all consumers who purchase the product in the first period upgrade to the high-end product in the second period. Hence, the firm can obtain profits from the low-end and high-end products without any loss in efficiency due to cannibalization. Comparing the profits numerically for different values of $\delta$ proves the proposition.

**Result 4**: In the simultaneous introduction case, the Nash equilibrium prices for the low-end product and high-end product are:

$$p_1 = \frac{q_1}{4q_2 - q_1}[cq_2^2 + 2cq_1q_2 + q_2 - q_1]$$

$$p_2 = \frac{2q_2}{4q_2 - q_1}[cq_2^2 + 2cq_1q_2 + q_2 - q_1] - cq_1q_2$$

In the sequential upward introduction case, the Nash equilibrium prices for the low-end product and high-end product are:

$$p_1 = \frac{q_1}{4\delta q_2 - q_1}[\delta cq_2^2 + 2\delta cq_1q_2 + \delta q_2 - q_1]$$

$$p_2 = \frac{q_2}{4\delta q_2 - q_1}[2\delta cq_2^2 + cq_1^2 + 2\delta q_2 - 2q_1]$$

In the sequential downward introduction case, the Nash equilibrium prices for the low-end product and high-end product are:

$$p_1 = \frac{q_1}{4q_2 - \delta q_1}[cq_2^2 + 2\delta cq_1q_2 + q_2 - \delta q_1]$$

$$p_2 = \frac{q_2}{4q_2 - \delta q_1}[2cq_2^2 + \delta cq_1^2 + 2q_2 - 2\delta q_1] \qquad \square$$

*A.5. Proof of Result 4*

We present the case for the sequential upward introduction case, the proof for the other two cases is analogous. Since $v_1q_1 = p_1$ and $v_2q_2 - p_2 = (1/\delta)(v_2q_1 - p_1)$, it follows that $v_1 = (p_1/q_1)$ and $v_2 = (\delta p_2 - p_1)/(\delta q_2 - q_1)$. The two profit functions are given by

$$\Pi_1 = \left[\frac{\delta p_2 - p_1}{\delta q_2 - q_1} - \frac{p_1}{q_1}\right](p_1 - cq_1^2), \quad \Pi_2 = \delta\left[1 - \frac{\delta p_2 - p_1}{\delta q_2 - q_1}\right](p_2 - cq_2^2)$$

The first-order condition of $(\partial \Pi_1/\partial p_1) = 0$ gives us

$$\frac{\delta p_2 - p_1}{\delta q_2 - q_1} - \frac{p_1}{q_1} = (p_1 - cq_1^2)\left(\frac{1}{\delta q_2 - q_1} + \frac{1}{q_1}\right) \quad \text{and} \quad \frac{\partial \Pi_2}{\partial p_2} = 0$$

gives us

$$1 - \frac{\delta p_2 - p_1}{\delta q_2 - q_1} = \delta \frac{p_2 - cq_2^2}{\delta q_2 - q_1}$$

respectively. The two conditions reduce to

$$p_2 = \frac{q_2}{q_1}(2p_1 - cq_1^2); \text{ and } 2\delta p_2 = p_1 + \delta cq_2^2 + \delta q_2 - q_1$$

Solving these two linear equations simultaneously gives us the equations in Result 4. $\square$

*A.6. Proof of Proposition 3*

For the simultaneous introduction case, substituting the Nash equilibrium prices $p_1$ and $p_2$ back into the profit functions, we get:

$$\Pi_1 = q_1 q_2 (q_2 - q_1) \left[ \frac{1 + cq_2 - cq_1}{4q_2 - q_1} \right]^2$$

and

$$\Pi_2 = (q_2 - q_1) \left[ \frac{2q_2 - 2cq_2^2 - cq_1 q_2}{4q_2 - q_1} \right]^2$$

Differentiating $\Pi_1$ and $\Pi_2$ with respect to $q_1$ and $q_2$ gives us the following two equations:

$$(q_2 - 2q_1)(4q_2 - q_1)[1 + c(q_2 - q_1)] - 2q_1(q_2 - q_1)[1 - 3cq_2] = 0$$
$$q_2(4q_2 - q_1)[1 - c(q_2 + \frac{q_1}{2})] + (q_2 - q_1)[cq_1^2 - 2q_1(1 - 2cq_2) - 8cq_2^2] = 0$$

Solving the above two equations simultaneously gives us the results of Proposition 3. For the sequential upward introduction case, the two profit functions are given by

$$\Pi_1 = \frac{q_1 \delta q_2 (\delta q_2 - q_1)}{(4\delta q_2 - q_1)^2} \left[ c(\delta q_2 - q_1) + 1 + \frac{\delta(1 - \delta)cq_2^2}{\delta q_2 - q_1} \right]^2$$
$$\Pi_2 = \left[ \frac{(\delta q_2 - q_1)2\delta q_2 - (2\delta q_2 - q_1)\delta cq_2^2 - \delta cq_1^2 q_2}{(4\delta q_2 - q_1)}^2 (\delta q_2 - q_1) \right] q_2[2\delta q_2 - 2q_1 - 2\delta cq_2^2 + cq_1^2 + cq_1 q_2]$$

A numerical comparison of the profits from the different solutions dependent on $\delta$ provides the results of the proposition. □

*A.7. Proof of Proposition 4*

For the sequential downward introduction case, the problem is specified as follows: Firm 2:

$$\text{Max}\, \Pi_2 = (1 - v_2)(p_2 - cq_2^2)$$
$$v_2 q_2 - p_2 \geqslant 0$$

Since customers do not have foresight, we get $v_2 = (p_2/q_2)$ from the constraint. Substituting this value in the profit function, we get $v_2 = 0.67$. The low-end product can then be sold potentially in third period to all customers with valuations between 0 and 0.67. Hence, the problem for the low-end product is as follows: Firm 1:

$$\text{Max}\, \Pi_1 = \left( \frac{2}{3} - v_1 \right) (p_1 - cq_1^2)$$
$$v_1 q_1 - p_1 \geqslant 0.$$

Solving for $v_1$, we obtain $v_1 = 0.44$. The profits for firm 2 from the high-end product are $\Pi_2 = 1/27c$, while the profits for firm 1 from the low-end product are $\Pi_1 = 8/729c$, which makes the high-end product more profitable.

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