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# R&D Competition Between an Incumbent and an Entrant: An Integrated Model of R&D Investment, Performance Improvement, and Time-to-Market

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#### Abstract

In this paper, we set up a game theoretical model in which an incumbent and an entrant choose their respective R&D strategies to compete with each other. Our paper contributes to three major debates regarding a firm's R&D strategy; the incumbent's and the entrant's choice between a radical R&D project and an incremental one, the incumbent's decision of whether to pre-empt the entrant, and the trade-off between product quality improvement and time-to-market. Our model considers three decisions that both the entrant and the incumbent need to make: (1) the amount of investment in the R&D project, (2) timing of new product introduction, and (3) the magnitude of performance improvement. These three decisions completely define a firm's R&D strategy. As for the product performance improvement, the entrant has to decide whether to introduce an incrementally improved product or a drastically improved one. With the incrementally improved product, the entrant can enter the market earlier at a low R&D cost, but it will lag behind the incumbent in product performance. On the other hand, with the drastically improved product, the entrant may be able to leapfrog the incumbent in product performance, but the downside is that the entry needs to be delayed or more investment in the R&D project is needed. The entrant's strategy is further affected by the incumbent's potential reaction. The incumbent, anticipating the entrant's entry, can react by either improving its product incrementally or drastically. The incumbent can even pre-empt the entrant's entry by introducing its new product before the entry occurs. We find that, when trading off time-to-market against quality improvement, both the incumbent and the entrant should emphasize quality improvement over time-tomarket. Specifically, the entrant should enter the market with a drastically improved new product, even if it means that the entry has to be delayed. The incumbent, anticipating the entrant's move, should react by introducing a drastically improved new product as well. Therefore, in the debate about the relative importance of time-to-market and quality improvement, we side with the school of thoughts that emphasizes the latter. Furthermore, we find that there is no need for the incumbent to pre-empt the entrant's move, i.e., the incumbent should introduce its new product only after entry even if it is certain about entry at the very beginning. This is different from Gilbert and Newbery's (1982) finding that the incumbent should pre-empt the entrant, and it is also different from Kamien and Schwartz (1972) who show that the incumbent will delay its R&D indefinitely in the face of competition. As for the incumbent's and the entrant's choices of either a radical innovation or an incremental one, our finding is consistent with the conventional wisdom that the entrant should introduce a radically innovative product (Day and Shoemaker 2000). However, our findings on the incumbent's choice of R&D project differ from any existing studies that advocate a cautious approach (e.g., Reinganum 1983). In recent years, many leading companies in various industries have come to the same conclusion and began to invest in more drastic R&D projects (see Chandy and Tellis 2000), as advocated by our findings. Our findings are also different from other studies in that we have produced clear and easy-tounderstand findings. In contrast, many existing studies (e.g., Ali, Kalwani and Kovenock 1993; Cohen, Eliashberg, and Ho 1996; Bayus, Jain and Rao 1997) provide more nuanced but also ambiguous results that depend on market conditions that are difficult to empirically validate. The intuition for our major finding that both the incumbent and the entrant should engage in radical R&D projects is relatively straightforward. Consider the entrant first. If the entrant enters the market with an incrementally improved product, such is not forceful enough to challenge the incumbent's dominant position; hence, it is a dominated strategy by a drastic R&D project. And, knowing that the entrant's product will be always drastically improved, the

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#### Keywords

Competitive Strategy; New Product; Introduction Strategy; Time-to-Market; Game Theory.

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## R&D Competition Between an Incumbent and an Entrant:

## An Integrated Model of R&D Investment, Performance Improvement, and

Time-to-Market \*

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April 2003

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We find that, when trading off time-to-market against quality improvement, both the incumbent and the entrant should emphasize quality improvement over time-to-market. Specifically, the entrant should enter the market with a drastically improved new product, even if it means that the entry has to be delayed. The incumbent, anticipating the entrant's move, should react by introducing a drastically improved new product as well. Therefore, in the debate about the relative importance of time-to-market and quality improvement, we side with the school of thoughts that emphasizes the latter. Furthermore, we find that there is no need for the incumbent to pre-empt the entrant's move, i.e., the incumbent should introduce its new product only after entry even if it is certain about entry at the very beginning. This is different from Gilbert and Newbery's (1982) finding that the incumbent should pre-empt the entrant, and it is also different from Kamien and Schwartz (1972) who show that the incumbent will delay its R&D indefinitely in the face of competition. As for the incumbent's and the entrant's choices of either a radical innovation or an incremental one, our finding is consistent with the conventional wisdom that the entrant should introduce a radically innovative product (Day and Shoemaker 2000). However, our findings on the incumbent's choice of R&D project differ from many existing studies that advocate a cautious approach (e.g., Reinganum 1983). In recent years, many leading companies in various industries have come to the same conclusion and began to invest in more drastic R&D projects (see Chandy and Tellis 2000), as advocated by our findings. Our findings are also different from other studies in that we have produced clear and easy-to-understand findings. In contrast, many existing studies (e.g., Ali, Kalwani and Kovenock 1993; Cohen, Eliashberg, and Ho 1996; Bayus, Jain and Rao 1997) provide more nuanced but also ambiguous results that depend on market conditions that are difficult to empirically validate.

The intuition for our major finding that both the incumbent and the entrant should engage in radical R&D projects is relatively straightforward. Consider the entrant first. If the entrant enters the market with an incrementally improved product, such an entry is not forceful enough to challenge the incumbent's dominant position; hence, it is a dominated strategy by a drastic R&D project. And knowing that the entrant's product will be always drastically improved, the incumbent should react likewise to protect its leadership position. The optimal entry time for the entrant and the reaction time for the incumbent are determined according to the trade-off of R&D costs and firm profits, and in equilibrium, the incumbent will not pre-empt entry to minimize its R&D costs. We also study the scenario where the incumbent does not anticipate the entry. In this case, in order to take advantage of the incumbent's delayed reaction, the entrant should accelerate its entry but should not change its product strategy, that is, it should still introduce a drastically improved new product. Although being caught off guard by the entrant's surprise entry, the incumbent should not react hastily. Rather, it should proceed with the same pace in its R&D process as in the previous case and introduce a drastically improved new product.

<u>Key Words</u>: Competitive Strategy; New Product; Introduction Strategy; Time-to-Market; Game Theory.

#### 1. Introduction

The importance of new products has long been recognized by researchers and practitioners alike. Hence, a firm's R&D strategy for new product development has received much attention in the economics and marketing literatures. In any R&D project, two decisions are especially important: time to introduce the new product and product performance improvement. Ideally, the new product should represent a major improvement in product quality over the existing one, and it should be introduced in a timely fashion. However, given a fixed investment in the R&D project, the firm has to make a trade-off between time-to-market and quality improvement. The firm can either expedite the product introduction at the expense of product performance or introduce a higher quality product by delaying the introduction time. One school of thoughts advocates the importance of time-to-market dimension. A McKinsey study reports that, on average, a six-month delay in product shipment will cost companies 33% of after-tax profits. Smith and Reinertsen (1991) argue for an incremental approach to product innovation because this will reduce the amount of time needed to develop the new product. An alternative school of thoughts emphasizes the importance of product performance. Zirger and Maidique (1990), based on a sample of new products in the electronics industry, show that product performance significantly affects product profitability. Cooper and Kleinschmidt (1987) demonstrate that product superiority in terms of unique features, innovativeness, and performance, is a key factor that differentiates new product winners from losers. Unfortunately, product quality improvement takes more time to develop and can significantly delay the product launch (see Griffin 1997 for empirical evidence).

The firm's R&D strategy is further complicated by competition. Most new product development projects take place in a competitive environment, which makes the trade-off

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between time-to-market and quality improvement even more difficult for the firm. The consequence of being second to the market in a technology race may be a permanent disadvantage to the market leader. On the other hand, rushing to the market with an immature technology can lead to disaster, for the pioneer can be easily overtaken by the second mover's superior technology. The existing research has produced mixed and often ambiguous findings. Kamien and Schwartz (1972) find that competition will cause the firm to postpone its R&D project indefinitely. Ali, Kalwani, and Kovenock (1993) show that the competing firms may choose the same or different R&D projects (either incremental or drastic) depending on the profit rates that will accrue to new products. However, they do not consider the time-to-market dimension endogenously, thus avoiding the issue of trade-off. Cohen, Eliashberg, and Ho (1996) explicitly consider the trade-off and show that the optimal time-to-market and product performance target depend on parameters relating to the firm's cost structure and market characteristics. However, competition is exogenous in their model. Bayus, Jain and Rao (1997) have developed a game theoretical model that explicitly considers quality improvement and time-to-market in a competitive environment and find that the leader prefers to introduce a higher-performance product at an earlier time than the follower. In other words, the leader will invest more in its R&D project to avoid the trade-off. However, Bayus, Jain and Rao exogenously determine the firms' status as leader and follower, hence, the important issue of time-to-market in a technology race is essentially avoided in their model.

In the studies that consider competition explicitly, the competing firms are often assumed to start their respective R&D projects simultaneously at time zero (e.g., Ali, Kalwani, and Kovenock 1993; Bayus, Jain and Rao 1997). However, in the real world, symmetry is often the exception rather than the norm. For example, Charles Schwab & Co. is the first retail investment

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firm that offered online investment services. Recognizing the potential of this new investment channel, Fidelity competed with Charles Schwab to develop software for its retail-brokerage customers to use in making investments online. As reported in *BusinessWeek*:<sup>1</sup>

When Fidelity began the software-development effort, says CIO Albert Aiello, "we knew Schwab was coming out with something, and we wanted to jump right over them. We tried to do too much." Aiello won't disclose how much was spent on the project, but only 40,000 Fidelity brokerage clients---out of 1.6 million---use it today.

While Fidelity stumbled, Schwab expanded its lead, signing up several hundred thousand customers to its proprietary software. Last May, Schwab widened the gap by launching Internetbased equity trading. Today, 24% of all trades executed by the San Francisco giant are done through its PC software. Fidelity plans to launch Internet trading by the end of the year.

Microsoft faced a similar problem when it tried to catch up with Netscape in the category of Internet browsing software. Netscape was the innovator with its Navigator software for Web browsing. In a frantic race with the market leader, Microsoft released four successive versions of Explorer in a little more than a year in 1997. However, its market share was still far behind Netscape's estimated 80%.<sup>2</sup> Microsoft's Explorer did not gain significant market share until it was much improved in performance at a much later date.<sup>3</sup> Therefore, R&D competition between a market incumbent and a potential entrant represents a more realistic picture than that between two symmetric firms. In this paper, we study just such a situation.

Research on competition between a incumbent and an entrant does not yield clear findings. One school of thoughts suggests that the incumbent, being the leader in the

<sup>&</sup>lt;sup>1</sup> October 28, 1996, p. 134.

<sup>&</sup>lt;sup>2</sup> Reported in New York Times, March 10, 1997.

marketplace, tends to be more conservative in its new product effort. A common perception in the field is that incumbent firms rarely introduce radical product innovations. Such firms tend to solidify their market positions with relatively incremental innovations (Christensen 1997; Ghemawat 1991; Henderson 1993). Reinganum (1983) shows that the incumbent invests less than the entrant in R&D because the incumbent, already having an innovative product, has less to gain from product improvement. However, Gilbert and Newbery (1982) show the opposite finding: the incumbent will invest more in R&D to pre-empt the entrant. In both papers, the authors exogenize quality improvement through patents; hence, the trade-off between quality improvement and time-to-market is not considered. In an empirical investigation, Chandy and Tellis (2000) find that, in recently years, incumbents are more likely to introduce radical innovations than non-incumbents. Furthermore, the innovations introduced by incumbents are no less radical than those introduced by non-incumbents.

In this paper, we set up a game theoretical model in which an incumbent and an entrant choose their respective R&D strategies to compete with each other. Our paper contributes to three major debates regarding a firm's R&D strategy: the incumbent's and the entrant's choices between a radical R&D project and an incremental one, the incumbent's decision of whether to pre-empt the entrant, and the trade-off between product quality improvement and time-to-market. Our model considers three decisions that both the entrant and the incumbent need to make: (1) the amount of investment in the R&D project, (2) timing of new product introduction, and (3) the magnitude of performance improvement. These three decisions completely define a firm's R&D strategy. As for the product performance improvement, the entrant has to decide whether to introduce an incrementally improved product or a drastically improved one. With the

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<sup>&</sup>lt;sup>3</sup> For a detailed analysis of the browser war between Microsoft and Netscape, see Windrum (2001).

incrementally improved product, the entrant can enter the market earlier at a low R&D cost, but it will lag behind the incumbent in product performance. On the other hand, with the drastically improved product, the entrant may be able to leapfrog the incumbent in product performance, but the downside is that the entry needs to be delayed or more investment in the R&D project is needed. The entrant's strategy is further affected by the incumbent's potential reaction. The incumbent, anticipating the entrant's entry, can react by either improve its product incrementally or drastically. The incumbent can even pre-empt the entrant's entry by introducing its new product before the entry occurs.

In many a case, the incumbent is fully aware of the entrant's intention to enter the market so it can react to the entry even before it occurs. For example, Netscape had been fully aware that Microsoft was developing an Internet browser software program to compete in the browser market. In this case, the entrant is under greater pressure to rush to the market and/or to improve its product quality drastically. In other cases, the incumbent is not aware of the existence of the entrant and it will be caught off guard when the entry occurs. If this is true, how should a *stealth* entrant change its entry strategy? Should it delay its entry time and/or introduce an incrementally improved new product?

In addition to the fact that we consider competition explicitly in a game theoretical approach, unlike, say, Kamien and Schwartz (1972) and Cohen, Eliashberg, and Ho (1996), one major difference between our paper and the R&D literature is that our paper considers a complete R&D strategy, i.e., we consider all three decisions—R&D investment, time-to-market, and quality improvement, simultaneously and endogenously. In contrast, many of the existing studies only consider two of the three decision variables mentioned above. For example, Kamien and Schwartz (1972), Reinganum (1985), and Fethke and Birch (1982) consider both the timing

and the cost of R&D activities, but ignore performance improvement. Rao and Rutenberg (1979) consider a firm's timing of building a plant when competing with a rival. Dasgupta and Stiglitz (1980) consider the cost of R&D activities and associated performance improvement in the form of marginal cost reduction (rather than of quality improvements considered in our model,) but they do not deal with the timing of new product introduction. Another critical difference between our model and the existing literature is that, in our model, all three decision variables are determined jointly as a best response to the other firm's strategies, that is, they are all endogenous in the game. In particular, the R&D cost is endogenized in the model. In contrast, most research treats one or two of the three decision variables exogenously, with the timing of introduction most frequently assumed to be exogenously determined in the form of probability distributions (Reinganum 1985, Kamien and Schwartz 1972, and Ali, Kalwani and Kovenock 1993 use exponential distributions, and Fethke and Birch 1982 use a distribution with increasing hazard rate.) Although the time needed to complete certain R&D projects such as the discovery of a new drug may indeed be random, many other R&D projects, especially those in high-tech industries, have very definite completion dates that are under the firms' control. Indeed, hightech firms are often able to pre-announce the introduction time of new products. For example, Microsoft announced the introduction date for its Windows 95 operating system long before the actual launch. The existing literature also often treats the cost of an R&D project as an exogenous variable, (Ali, Kalwani and Kovenock 1993 and Dasgupta and Stiglitz 1980). These assumptions, although mathematically convenient, avoid the strategic issue of the trade-off between time-to-market and product quality improvement under certain budget constraint.

We find that, when trading off time-to-market against quality improvement, both the incumbent and the entrant should emphasize quality improvement over time-to-market.

Specifically, the entrant should enter the market with a drastically improved new product, even if it means that the entry has to be delayed. The incumbent, anticipating the entrant's move, should react by introducing a drastically improved new product as well. Therefore, in the debate about the relative importance of time-to-market and quality improvement, we side with the school of thoughts that emphasizes the latter. Furthermore, we find that there is no need for the incumbent to pre-empt the entrant's move, i.e., the incumbent should introduce its new product only after entry even if it is certain about entry at the very beginning. This is different from Gilbert and Newbery's (1982) finding that the incumbent should pre-empt the entrant, and it is also different from Kamien and Schwartz (1972) who show that the incumbent will delay its R&D indefinitely in the face of competition. As for the incumbent's and the entrant's choices of either a radical innovation or an incremental one, our finding is consistent with the conventional wisdom that the entrant should introduce a radically innovative product (Day and Shoemaker 2000). However, our findings on the incumbent's choice of R&D project differ from many existing studies that advocate a cautious approach (e.g., Reinganum 1983). In recent years, many leading companies in various industries have come to the same conclusion and began to invest in more drastic R&D projects (see Chandy and Tellis 2000), as advocated by our findings. Our findings are also different from other studies in that we have produced clear and easy-to-understand findings. In contrast, many existing studies (e.g., Ali, Kalwani and Kovenock 1993; Cohen, Eliashberg, and Ho 1996; Bayus, Jain and Rao 1997) provide more nuanced but also ambiguous results that depend on market conditions that are difficult to empirically validate.

The intuition for our major finding that both the incumbent and the entrant should engage in radical R&D projects is relatively straightforward. Consider the entrant first. If the entrant enters the market with an incrementally improved product, such an entry is not forceful enough

to challenge the incumbent's dominant position; hence, it is a dominated strategy by a drastic R&D project. And knowing that the entrant's product will be always drastically improved, the incumbent should react likewise to protect its leadership position. The optimal entry time for the entrant and the reaction time for the incumbent are determined according to the trade-off of R&D costs and firm profits, and in equilibrium, the incumbent will not pre-empt entry to minimize its R&D costs. We also study the scenario where the incumbent does not anticipate the entry. In this case, in order to take advantage of the incumbent's delayed reaction, the entrant should accelerate its entry but should not change its product strategy, that is, it should still introduce a drastically improved new product. Although being caught off guard by the entrant's surprise entry, the incumbent should not react hastily. Rather, it should proceed with the same pace in its R&D process as in the previous case and introduce a drastically improved new product.

Our finding suggests that Microsoft, when attempting to enter the Internet browser market, should invest a substantial amount of resources to develop a new product that can surpass Netscape Communications in product performance, even if this means that Microsoft would have to delay the introduction of such a product. Ironically, Microsoft adopted the strategy suggested by our model when it introduced Windows 95 operating system and Windows-based spreadsheet software Excel, that is, both were introduced with great improvement but at a much delayed time. These two products have achieved great success in the marketplace.

The rest of the paper is organized as follows. We describe the model and necessary assumptions in Section 2. Section 3 analyzes the entrant's and the incumbent's R&D strategies in equilibrium when the entrant's existence is known and Section 4 analyzes the same problem

when its existence is not known. We consider the close-loop solution in Section 5 and discuss the results and conclude in Section 5.

#### 2. The Model

The market is currently occupied by a monopolist firm, called the incumbent. An entrant is considering whether to enter the market or not. To enter the market, it has to first develop a product by undertaking an R&D project. The incumbent's reaction to the entry involves developing its own new product by undertaking an R&D project. We consider two scenarios in this paper. First, the incumbent is aware of the entrant's existence and its intention to enter the market. In this case, the incumbent can start its R&D project even before the entry occurs. We call this the *simultaneous game* because the entrant and the incumbent begin their respective R&D projects roughly at the same time. This strategy is similar in spirit to the incumbent's strategy of preparing R&D projects as contingency plans to react to potential entries. IBM used such a strategy when competing for better disk drives. The second scenario deals with an incumbent who is ignorant of the existence of the entrant. In this case, the incumbent will not react to the entry by undertaking an R&D project until it actually occurs. We call this the *sequential game*.

We use an infinite time horizon instead of imposing an arbitrary fixed time window (e.g., Cohen, Eliashberg, and Ho 1996; Wilson and Norton 1989). And the two firms' strategies depend on two relationships: the relationship between R&D investment and product performance/time-to-market, and the relationship between product performance and profits.

#### 2.1. R&D Investments

The amount of R&D investment will determine product performance and the timing of introduction. With a fixed amount of investment in R&D, the entrant can either expedite the

product introduction at the expense of product performance or introduce a higher quality product by delaying the introduction time. A larger investment is needed if both a better product and an earlier introduction are desired. The model assumes that the R&D investment is irreversible.

First, the R&D cost is increasing in quality improvement. A radically improved product is more costly to develop than an incrementally improved one because the former requires more financial and human resources. Second, R&D cost savings can be achieved by delaying introduction for two reasons. The first is the time value of money (opportunity cost). The larger the discount factor, the greater the possible savings will accrue when the completion date is postponed. The second is the inverse time-cost trade-off studied by Scherer (1967). Time compression of the R&D project requires hiring more technicians and engineers and/or using more state-of-the-art equipment. Hence, following Kamiem and Schwartz (1972), we use optimal control theory to develop the firm's R&D investment.<sup>4</sup>

Suppose a firm's existing product has a quality level of  $v_0$ . It intends to improve its quality to v' by time T,  $v' > v_0$ . Let y(t) denote the effort exerted at time t. Then, to improve quality by  $\Delta v (\equiv v' - v_0)$  by time T, it is necessary that the cumulative effort should achieve this goal, that is,  $\int_0^T y(t) dt = \Delta v$ . The cost of effort is assumed to be increasing and convex in the effort level. Specifically, it is postulated that the cost of effort is  $c(t) = y^2(t)$ . The firm's

<sup>&</sup>lt;sup>4</sup> The key difference between our setup and Kamien and Schwartz's is that we explicitly consider quality improvement. In the literature, R&D investment is determined by several ways. In Gilbert and Newbery (1982), the R&D investment equals the entrant's discounted profit due to free entry, which reduces the entry's net profit to zero. Reinganum (1983) uses a constant R&D investment rate. Cohen, Eliashberg, and Ho (1996) assume that the total R&D investment is a function of development team size and wage rate. Bayus, Jain, and Rao (1997) use a additively separable functional form in time-to-market and quality improvement.

objective is to determine the effort rate y(t) to minimize its R&D cost by solving the following problem:

$$\min_{y(t)} \int_0^T e^{-\delta t} y^2(t) dt,$$

$$s.t. \mathbf{Y}(0) = 0, \int_0^T y(t) dt = \Delta v, \ y(t) \ge 0,$$
(1)

where  $\delta$  is the discount factor. This is a standard dynamic control problem, and the solution is

$$y(t) = \frac{\delta \Delta v}{e^{\delta T} - 1} e^{\delta t} \, .$$

(See Appendix A for proof). Substituting the above result into (1), we find that the total R&D cost is

$$C(\Delta v, T) = \frac{\delta}{e^{\delta T} - 1} \Delta v^2.$$
<sup>(2)</sup>

Clearly, with a fixed amount of capital available for product development, there are many different feasible combinations of  $\Delta v$  and *T*.

We assume that neither the entrant nor the incumbent can alter its R&D project upon observing the new product introduced by the opponent. It must continue with its chosen R&D project. Essentially, we search for an open-loop solution, which is the standard model assumption used in the literature (Reinganum 1981, Ali, Kalwani, and Kovenock 1993, Bayus, Jain, and Rao 1997). This assumption can be justified on the basis that switching to a different R&D project is prohibitively costly. We believe that open-loop policies are a close approximation of most R&D projects because of the long and involved nature of the new product development process.

Next, we characterize the firms' profit functions.

#### 2.2. Profit Function

We start by considering the entrant's and the incumbent's profit after entry occurs. Each firm's profit depends on its own and the competing firm's product qualities. Denote the incumbent's quality by  $q_1$  and the entrant's by  $q_2$ . We postulate that the firm's profit *rate* at any time is given by

$$\pi(q_i|q_j) = \frac{q_i}{q_i + q_j}, \ i, j, = 1, 2, \text{ and } i \neq j.$$
 (3)

An exogenously determined profit rate that depends on the product qualities such as (3) is used widely in the literature. For example, Ali, Kalwani and Kvenock (1993) and Reinganum (1983) simply use a constant profit rate, which is independent of the competing firm's product quality. In Kamien and Schwartz (1972), the profit rate is also exogenous, but it decays over time. In Bayus, Jain, and Rao (1997), the profit rate is a general function of both firms' product qualities. Hence, (3) can be viewed as a special functional form. Cohen, Eliashberg, and Ho (1996) use a functional form that is identical to (3). Actually, as shown in Cohen, Eliashberg, and Ho, (3) is a reduced functional form based on a demand function characterized by the logit model and constant profit margins for the two firms.<sup>5</sup> In many high-tech industries such as personal computers, firms essentially compete for market share while the profit margins remain constant more or less with ever-improved products. For example, prices for personal computers have

<sup>&</sup>lt;sup>5</sup> Specifically, after entry, consumers choose between two products whose qualities are  $q_1$  and  $q_2$ , respectively. According to the logit model, demand rate for product one is  $d_1 = \frac{e^{U(q_1)}}{e^{U(q_1)} + e^{U(q_2)}}$ , where U(q) is the deterministic component of the consumer's utility. Assume that  $U(q)=\ln(Q)$ , then  $d_1 = \frac{q_1}{q_1 + q_2}$ . Then, normalizing the constant profit margin to 1, we get (3).

ranged around \$2000 for over a decade, be it 386-based computers or Pentium-IV-based ones. It is clear from Figure 1, which illustrates gross profit margins for five major high-technology firms in recent years,<sup>6</sup> that their gross profit margins fluctuate within a narrow range over a long period of time. It should be noted that (3) is each firm's share of the total profit, and this normalization does not have any impact on our results. In particular, before entry, the incumbent's profit rate is normalized to 1 without any loss of generality.

#### [Figure 1 about here]

Suppose the incumbent is endowed with quality q before entry. The entrant's entry strategy consists of developing a product of quality  $\theta_2 q$  to be introduced at time  $t_2$ .<sup>7</sup> At the same time, anticipating entry, the incumbent decides to develop a new product whose performance is improved by  $\theta_1 q$  and will be introduced at  $t_1$  to *replace* the existing product.<sup>8</sup> Then the incumbent's new product's quality is  $(1+\theta_1)q$ . The incumbent can also choose not to react to entry, as indicated by  $\theta_1=0$ . Then its product quality remains q. Analogously,  $\theta_2=0$  means no entry. Without loss of generality, we make the normalizing assumption of q=1.<sup>9</sup> The entrant's and the incumbent's R&D investments are completely determined by  $S_2 = \{\theta_2, t_2\}$  and  $S_1 = \{\theta_1, t_1\}$ , respectively.

<sup>&</sup>lt;sup>6</sup> Data source: annual reports of the selected companies.

<sup>&</sup>lt;sup>7</sup> Throughout the paper, the entrant's variables are indexed by 2 and the incumbent's by 1.

<sup>&</sup>lt;sup>8</sup> In this paper, we do not consider the case where the incumbent's old and new products coexist with each other. Empirical evidence suggests that products of different *generations* usually do not coexist in most high technology industries.

 $<sup>^{9}</sup>$  If *q* is normalized to 0, it is equivalent to R&D competition between two symmetric entrants, a scenario studied by Ali, Kalwani, and Kovenock (1993) and Bayus, Jain, and Rao (1997). However, as discussed earlier, this is not an interesting and realistic scenario.

Since our focus in this paper is the trade-off between time-to-market and product improvement, we want to highlight the firm's strategic choice between a radical innovation and an incremental one. To this end, we discretize the choice of R&D projects for both firms by assuming that  $\theta_1, \theta_2 \in \{0, I, D\}, 0 < I < D$ , where *I* is the quality improvement associated with an incremental R&D project and *D* a drastic one.<sup>10</sup> It is important to note that a drastic R&D project is drastic only in the sense that its quality improvement is greater than an incremental one. It is not drastic in the sense that it will result in a new generation of technology such as digital camera as compared to traditional SLR camera. In the latter case, the profit function might well very be different from (3). Discretization of qualities is routinely used in the literature (for example, Ali, Kalwani, and Kovenock 1993 consider a truly innovative R&D project and a product modification project, analogous to a drastic R&D project and an incremental R&D project in our model.) Through comparative static analysis, we can examine a continuous range of *I* and *D* and its impact on our findings.

#### 3. The Simultaneous Game

In this game, the incumbent and the entrant start their respective R&D projects simultaneously. The simultaneity captures the feature that the incumbent anticipates the entrant's move and start to prepare its reaction even before entry occurs. The two firms' discounted profits over an infinite time horizon depend on each other's R&D strategies. Given four possibilities in their choices of R&D projects and whether the incumbent pre-empts the entrant or not, we need to consider eight scenarios. Consider the following scenario as an

<sup>&</sup>lt;sup>10</sup> If we allow a continuous range of product quality, it is hard to interpret the optimal choice of product quality as incremental, moderate, or drastic. Then, we are unable to provide clear insights for the firms to resolve the tradeoff. Similarly, we can also dichotomize the firms' choice of introduction time. Although this will significantly simplify the equilibrium analysis of the game, it will greatly compromise the external validity of our model.

example: the entrant decides to introduce a drastically improved product at time  $t_2$  and the incumbent decides to pre-empt the entrant by introducing an incrementally improved product at time  $t_1$ , that is, the incumbent's and the entrant's strategies are  $S_1 = \{I, t_1\}$  and  $S_2 = \{D, t_2\}$ , respectively, with  $t_1 \le t_2$ . This scenario is depicted in Figure 2. In this scenario, the incumbent's product quality is 1 before  $t_1$  and is increased to 1+I after  $t_1$ . At time  $t_2 (>t_1)$ , the entrant enters the market with a product of quality D. After entry, the entrant earns a profit rate of  $\pi(D|1+I)$ , hence its discounted profit, given the incumbent's strategy  $S_1 = \{I, t_1\}$ , is

$$\Pi_2(\{D,t_2\} | \{I,t_1\}) = \int_{t_2}^{\infty} \pi(D | 1+I) e^{-\delta t} dt - C(D,t_2), \ t_1 \le t_2.$$

For the incumbent, we need to consider three time intervals to calculate its discounted profit:  $[0, t_1), [t_1, t_2), [t_2, \infty)$ , corresponding to before pre-emption, between pre-emption and entry, and after entry. Its profit rates in the three intervals are  $\pi(1|0), \pi(1+I|0)$ , and  $\pi(1+I|D)$ , respectively; hence we can obtain the incumbent's discounted profit as

$$\Pi_1(\{I,t_1\}|\{D,t_2\}) = \int_0^{t_1} \pi(1|0)e^{-\delta t} dt + \int_{t_1}^{t_2} \pi(1+I|0)e^{-\delta t} dt + \int_{t_2}^{\infty} \pi(1+I|D)e^{-\delta t} dt - C(I,t_1), \ t_1 \le t_2.$$

For both firms, profit rate and R&D cost are given by (3) and (2), respectively.

#### [Figure 2 about here]

The two firms' discounted profits under other scenarios can be similarly obtained and, after simplification, are summarized in Table 1 for the incumbent and in Table 2 for the entrant.

#### [Tables 1 and 2 about here]

To proceed with the equilibrium analysis, we need to impose certain regularity conditions on parameters *I*, *D*, and  $\delta$  to restrict the analysis only to interesting cases. A major difference between an incremental R&D project and a drastic one is that the latter allows the entrant a

chance to leapfrog the incumbent in product quality whereas the former does not. Hence, we require that  $I \le 1$  and D > 1, (note that the incumbent's endowed product quality is normalized to 1). We further strengthen the condition on D to allow the entrant to leapfrog the incumbent if the incumbent does not react or reacts with only an incrementally improved new product. Hence, we require D > 1 + I. Combining these conditions, we have

$$I \le 1 \text{ and } D > 1 + I. \tag{4}$$

This means that  $I < \min[1, D-1]$ . We also impose a necessary condition in the baseline case that the entrant will enter the market with a drastically improved product if the incumbent does not react to the entry. Appendix B shows that this condition is satisfied if

$$\delta < \frac{1}{2(1+D)\sqrt{D(1+D)}}$$
 (5)

Condition (5) simply says that the discount factor has to be small enough so that the entrant can earn a positive discounted profit over time in the most optimistic scenario of no reaction from the incumbent. If (5) does not hold, the entrant will simply not enter the market regardless of the incumbent's reaction. We restrict our attention to the parameter space defined by regularity conditions (4) and (5). Next, we consider the incumbent's potential reactions first and the entrant's second.

#### 3.1. The incumbent's potential reactions

First, it is trivial to prove that no reaction is a dominated strategy for the incumbent. Thus, we only need to consider the incumbent's reaction with either *I* or *D*.

**Reaction to the entrant's incrementally improved product**. Note that the incumbent never wants to preempt entry if it knows the exactly entry time because such a move will not improve its profitability due to the profit function (3) but will increase the R&D cost. Therefore, in

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reaction to the entrant's strategy of  $\{I, t_2\}$ , the incumbent's R&D strategy is either  $\{I, t_1\}$  or  $\{D, t_1\}$ ,  $t_1 > t_2$ . If the reaction is  $\{I, t_1\}$ , according to Table 1, the incumbent's discounted profit is

$$\Pi_{1}(\{I,t_{1}\} | \{I,t_{2}\}) = \frac{1}{\delta} + \frac{1}{\delta} \frac{I^{2}}{(1+I)(1+2I)} e^{-\delta t_{1}} - \frac{1}{\delta} \frac{I}{1+I} e^{-\delta t_{2}} - \frac{\delta I^{2}}{e^{\delta t_{1}} - 1}$$

Then, the incumbent will maximize its discounted profit at

$$t_1^{(I,I)} = -\frac{1}{\delta} \ln \left[ 1 - \delta \sqrt{(1+I)(1+2I)} \right],\tag{6}$$

if  $t_1^{(I,I)} > t_2$  and at  $t_2$  otherwise. Superscript (I, I) refers to the incumbent's and the entrant's R&D projects, respectively.  $t_1^{(I,I)}$  is ensured to be positive due to (5). Given that the incumbent chooses to react to the entry with an incrementally improved new product, the incumbent should introduce its new product at  $t_1^{(I,I)}$  if the entrant enters early or introduce it at the same time when the entry occurs. The intuition is straightforward. If the entry occurs early, the strategy of rushing to the market in reaction will result in a large increase in R&D costs for the incumbent. If the entrant decides to enter at a later time, the incumbent can also delay its reaction to the exact time when the entry occurs. Note that  $t_1^{(I,I)}$  is independent of the entry time  $t_2$ .

If the incumbent decides to react with a drastically improved new product, according to Table 1, its discounted profit is

$$\Pi_{1}(\{D,t_{1}\} | \{I,t_{2}\}) = \frac{1}{\delta} + \frac{1}{\delta} \frac{ID}{(1+I)(1+I+D)} e^{-\delta_{1}} - \frac{1}{\delta} \frac{I}{1+I} e^{-\delta_{2}} - \frac{\delta D^{2}}{e^{\delta_{1}} - 1}$$

Hence, the incumbent will maximize its discounted profit at

$$t_1^{(D,I)} = -\frac{1}{\delta} \ln \left[ 1 - \delta \sqrt{\frac{D}{I} (1+I)(1+I+D)} \right],$$
(7)

if  $t_1^{(D,I)} > t_2$ , otherwise at  $t_2$ . In order for  $t_1^{(D,I)}$  to be positive, it is necessary that

$$\delta < \frac{1}{\sqrt{\frac{D}{I}(1+I)(1+I+D)}},\tag{8}$$

which is satisfied if *I* is not too small. Obviously, when *I* is too small, the entrant's new product does not pose a big threat to the incumbent, so  $\{D, t_1\}$  is an overreaction. Combining these two scenarios, we have the following proposition (proved in Appendix C):

**Proposition 1.** In response to the entrant's strategy  $\{I, t_2\}$ , the incumbent's reaction should be:

- 1. If I is small enough, that is, if condition (8) is not satisfied, the incumbent should introduce an incrementally improved new product. The product should be introduced at  $t_1^{(I,I)}$  if  $t_1^{(I,I)} > t_2$  and at  $t_2$  otherwise.
- 2. If condition (8) is satisfied, the incumbent should introduce a drastically improved new product. The product should be introduced at  $t_1^{(D,I)}$  if  $t_1^{(D,I)} > t_2$  and at  $t_2$  otherwise.

**Reaction to the entrant's drastically improved product.** Parallel to the previous case, we can obtain the incumbent's optimal introduction time by using appropriate profit functions in Table 1. Specifically, if the incumbent reacts by introducing an incrementally improved product, its discounted profit is maximized at

$$t_1^{(I,D)} = -\frac{1}{\delta} \ln \left[ 1 - \delta \sqrt{\frac{I(1+D)(1+I+D)}{D}} \right],$$

if  $t_1^{(I,D)} > t_2$  and at  $t_2$  otherwise. If the incumbent reacts by introducing a drastically improved product, its discounted profit is maximized at

$$t_1^{(D,D)} = -\frac{1}{\delta} \ln \left[ 1 - \delta \sqrt{(1+D)(1+2D)} \right], \tag{9}$$

if  $t_1^{(D,D)} > t_2$ , otherwise at  $t_2$ . Both  $t_1^{(I,D)}$  and  $t_1^{(D,D)}$  are positive because of the regularity condition (5). Then, we can summarize the following result (proved in Appendix C):

**Proposition 2**. In response to the entrant's entry with a drastically improved product at  $t_2$ , the incumbent should always respond by drastically improving its product and introducing the new product at  $t_1^{(D,D)}$  if  $t_1^{(D,D)} > t_2$  and at  $t_2$  otherwise.

#### 3.2. The entrant's strategy

When deciding whether to enter with an incrementally improved product or a drastically improved one, the entrant needs to anticipate the incumbent's reaction. Consider the incremental R&D strategy first.

Entry with an incrementally improved product. In this case, suppose the incumbent reacts to the entry by introducing an incrementally improved new product at  $t_1$ . The entrant's discounted profit depends on whether it is the first mover or not. If it enters the market before the incumbent's reaction, according to Table 2, its discounted profit is

$$\Pi_{2}(\{I,t_{2}\} | \{I,t_{1}\}) = \frac{1}{\delta} \frac{I}{1+I} e^{-\delta t_{2}} - \frac{1}{\delta} \frac{I^{2}}{(1+I)(1+2I)} e^{-\delta t_{1}} - \frac{\delta I^{2}}{e^{\delta t_{2}} - 1}$$

Hence, the entrant will maximize its discounted profit at

$$t_{2,1st}^{(I,I)} = -\frac{1}{\delta} \ln \left[ 1 - \delta \sqrt{I(1+I)} \right],$$

if  $t_{2,1st}^{(I,I)} \le t_1$ . The subscript *Ist* stands for the *first* mover. If  $t_{2,1st}^{(I,I)} \le t_1$  does not hold, the entrant will be the second mover. According to Table 2, its discounted profit is

$$\Pi_{2}(\{I,t_{2}\} | \{I,t_{1}\}) = \frac{1}{\delta} \frac{I}{1+2I} e^{-\delta t_{2}} - \frac{\delta I^{2}}{e^{\delta t_{2}}-1}.$$

Hence, the entrant will maximize its discounted profit at

$$t_{2,2nd}^{(I,I)} = -\frac{1}{\delta} \ln \Big[ 1 - \delta \sqrt{I(1+2I)} \Big],$$

if  $t_{2,2nd}^{(I,I)} > t_1$ . Both  $t_{2,1st}^{(I,I)}$  and  $t_{2,2nd}^{(I,I)}$  are positive due to condition (5), and we can prove that  $t_{2,1st}^{(I,I)} < t_{2,2nd}^{(I,I)}$ .

To completely determine the entrant's introduction time, divide the incumbent's reaction time into three intervals:  $[0, t_{2,1st}^{(I,I)}], (t_{2,1st}^{(I,I)}, t_{2,2nd}^{(I,I)}], and (t_{2,2nd}^{(I,I)}, \infty)$ . In the first interval, the entrant does not want to be the first mover as the incumbent's swift reaction does not make an early introduction profitable. Hence, the entrant will introduce its new product at  $t_{2,2nd}^{(I,I)}$  after the incumbent's preemptive move. In the third interval, the entrant wants to move ahead of the incumbent at  $t_{2,1st}^{(I,I)}$  when the incumbent's reaction is much delayed. In the second interval, the entrant can be either the first mover or the second mover. Comparing its profits with these two strategies, the entrant will move first if

$$t_1 > t_2^{(I,I)} \equiv -\frac{1}{\delta} \ln \left[ 1 - 2\delta \left[ (1 + 2I) \sqrt{\frac{1+I}{I}} - (1+I) \sqrt{\frac{1+2I}{I}} \right] \right],$$

and move second otherwise. And it is easy to check that  $t_{2,1st}^{(I,I)} < t_2^{(I,I)} < t_{2,2nd}^{(I,I)}$ .

Now consider the incumbent's reaction of introducing a drastically improved new product. Similarly, we consider whether the entrant moves first or second. By using appropriate profit functions in Table 2, we can derive the entrant's optimal entry time. Specifically, as a first mover, it should introduce its new product at the same time as in (*I*, *I*), i.e.,  $t_{2,1st}^{(D,I)} = t_{2,1st}^{(I,I)}$  if

 $t_{2,1st}^{(D,I)} \le t_1$ . As a second mover, the entrant's optimal entry time is

$$t_{2,2nd}^{(D,I)} = -\frac{1}{\delta} \ln \Big[ 1 - \delta \sqrt{I(1+I+D)} \Big],$$

if  $t_1 \le t_{2,2nd}^{(D,I)}$ . Obviously,  $t_{2,2nd}^{(D,I)} > t_{2,1st}^{(D,I)}$ . Therefore, similar to the previous case, we divide the incumbent's reaction time into three intervals and conclude that the entrant will move first if

$$t_1 > t_2^{(D,I)} \equiv -\frac{1}{\delta} \ln \left[ 1 - \frac{2\delta}{D} \left[ (1+I+D)\sqrt{I(1+I)} - (1+I)\sqrt{I(1+I+D)} \right] \right],$$

and move second otherwise. Again, it is easy to check that  $t_{2,1st}^{(D,I)} < t_2^{(D,I)} < t_{2,2nd}^{(D,I)}$ . We summarize the results in the following proposition:

**Proposition 3.** Suppose the entrant decides to introduce an incrementally improved product. If the incumbent reacts with  $\{I, t_1\}$ , the optimal entry time is  $t_2 = t_{2,2nd}^{(I,I)}$  if  $t_1 \le t_2^{(I,I)}$  and  $t_2 = t_{2,1st}^{(I,I)}$ if  $t_1 > t_2^{(I,I)}$ . If the incumbent reacts with  $\{D, t_1\}$ , the optimal entry time is  $t_2 = t_{2,2nd}^{(D,I)}$  if  $t_1 \le t_2^{(D,I)}$  and at  $t_2 = t_{2,1st}^{(D,I)}$  if  $t_1 > t_2^{(D,I)}$ .

Entry with a drastically improved product. We have already established that the incumbent will always respond to such an entry by drastically improving its product (see Proposition 2), thus, we only need to analyze the entrant's optimal entry time when facing a drastic reaction from the incumbent. Parallel to the previous case, by using appropriate profit functions in Table 2, we can derive the optimal entry time. Specifically, if the entrant moves first, the optimal entry time is

$$t_{2,lst}^{(D,D)} = -\frac{1}{\delta} \ln \left[ 1 - \delta \sqrt{D(1+D)} \right].$$
(10)

If it moves second, the optimal entry time is

$$t_{2,2nd}^{(D,D)} = -\frac{1}{\delta} \ln \left[ 1 - \delta \sqrt{D(1+2D)} \right].$$

Similar to the analysis of the previous two cases, the entrant will move first if

$$t_1 > t_2^{(D,D)} \equiv -\frac{1}{\delta} \ln \left[ 1 - 2\delta \left[ (1 + 2D) \sqrt{\frac{1 + D}{D}} - (1 + D) \sqrt{\frac{1 + 2D}{D}} \right] \right],$$

and move second otherwise. Again, we have  $t_{2,1st}^{(D,D)} < t_2^{(D,D)} < t_{2,2nd}^{(D,D)}$ . The results are summarized in the following proposition.

**Proposition 4.** Suppose the entrant decides to introduce a drastically improved product. Since the incumbent will always react with a drastically improved product, the entrant's optimal entry time is  $t_2 = t_{2,2nd}^{(D,D)}$  if  $t_1 \le t_2^{(D,D)}$  and  $t_2 = t_{2,1st}^{(D,D)}$  if  $t_1 > t_2^{(D,D)}$ .

#### 3.3. Strategies in equilibrium

Given the entrant's and the incumbent's strategies described in Propositions 1 through 4, we now search for the Nash equilibrium in which each firm's strategy is the best response to the other firm's strategy. There are three pure-strategy Nash equilibrium candidates: (I, I), (D, I), and (D, D), where the first letter refers to the incumbent's choice of R&D project and the second letter the entrant's, each associated with certain introduction time. (I,D) is clearly not a Nash equilibrium according to Proposition 2.

We start with (I, I). This can be a Nash equilibrium only if *I* is sufficiently small, that is, if (8) is *not* satisfied. To determine the entrant's and the incumbent's introduction time, we rely on Propositions 1 and 3 to superimpose the two firms' reaction functions in Figure 3. It is easy to prove that  $t_1^{(I,I)} > t_2^{(I,I)}$  for any *I*, resulting in the two reaction functions intersecting each other at point *A* in Figure 2. This means that the two firms' introduction times represented by point *A* are best responses to each other under (I, I). Then, we can conclude that, with (I, I), the entrant will move first at  $t_{2,1st}^{(I,I)}$  and the incumbent second at  $t_1^{(I,I)}$ . Next, consider (D,I). If *I* is not too

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small, namely, when (8) is satisfied, the incumbent will introduce a drastically improved new product in response to the entrant's entry with an incrementally improved product, and the entrant knows this. Again, with  $t_1^{(D,I)} > t_2^{(D,I)}$ , the entrant will move first at  $t_{2,1st}^{(D,I)}$  and the incumbent second at  $t_1^{(D,I)}$ . For the third case of (D, D), since  $t_1^{(D,D)} > t_2^{(D,D)}$ , in equilibrium, the incumbent will introduce the drastically improved new product at  $t_1^{(D,D)}$ , after the entrant enters the market at  $t_{2,1st}^{(D,D)}$ .

#### [Figure 3 about here]

With the entrant's and the incumbent's strategies completely defined in the three Nash equilibrium candidates, we can summarize their profits in Table 3. This table will be useful in our search for Nash equilibrium.

#### [Table 3 about here]

We study each of the three equilibrium candidates to verify whether any of them is a Nash equilibrium. For (I, I), consider the entrant's incentive to deviate. Given the incumbent's reaction  $\{I, t_1^{(I,I)}\}$ , the entrant can deviate to a different introduction time or a drastically improved product at certain time. Clearly, according to Proposition 3, deviation to a different introduction time will make the entrant worse off. On the other hand, if the entrant deviates by introducing a drastically improved product, then by using its discounted profit under (I, D) given in Table 2, we can show that it will enter the market after the incumbent's introduction time  $t_1^{(I,I)}$  at

$$t_{2,dev}^{(I,D)} = -\frac{1}{\delta} \ln \left[ 1 - \delta \sqrt{D(1+I+D)} \right],$$

where the subscript dev stands for deviation, and its discounted profit in deviation is

$$\Pi_{2,dev}^{(I,D)} = \frac{1}{\delta} \frac{D}{1+I+D} \Big[ 1 - \delta \sqrt{D(1+I+D)} \Big]^2.$$

Since the deviating profit  $\Pi_{2,dev}^{(I,D)}$  is greater than the non-deviating profit shown in Table 3 (the first row under the heading, proved in Appendix D), we can conclude that (I, I) is not a Nash equilibrium. This result is understandable because the entrant's long-run profit rate with (I, I), which is I/(1+2I), is less than that if it deviates to D, which is D/(1+I+D).

For (D, I), again, the entrant will not deviate to a different introduction time. If the entrant deviates to D, given the incumbent's strategy  $\{D, t_1^{(D,I)}\}$ , by using the entrant's discounted profit under (D, D) given in Table 2, we have  $t_1^{(D,I)} > t_{2,2nd}^{(D,D)} > t_2^{(D,D)}$ , hence, the entrant will enter the market at  $t_{2,1st}^{(D,D)}$ , and its profit is

$$\Pi_{2,dev}^{(D,D)} = \frac{1}{\delta} \frac{D \left[ 1 - \delta \sqrt{D(1+D)} \right]^2}{1+D} - \frac{1}{\delta} \frac{D^2 \left[ 1 - \delta \sqrt{\frac{D}{I}(1+I)(1+I+D)} \right]^2}{(1+D)(1+2D)}.$$

Compare this profit with that in Table 3 (the second row under the heading), again, it is easy to prove that the entrant's profit by deviating to D is greater than in (D,I), indicating that (D,I) is not a Nash equilibrium.

Lastly, for (D, D), as usual, the entrant has no incentive to deviate in introduction time. If it deviates to *I*, given the incumbent's reaction, its profit will be

$$\Pi_{2,dev}^{(D,I)} = \frac{1}{\delta} \frac{I \Big[ 1 - \delta \sqrt{I(1+I)} \Big]^2}{1+I} - \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+2D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+D)} \Big]^2}{(1+I)(1+I+D)} + \frac{1}{\delta} \frac{I D \Big[ 1 - \delta \sqrt{(1+D)(1+D)} \Big]^2}{(1+I+D)(1+D)} + \frac{1}{\delta} \frac{I$$

by noting that  $t_1^{(D,D)} > t_{2,2nd}^{(D,I)} > t_2^{(D,I)}$ . Obviously, the entrant is worse off by deviating to *I* from *D* according to Table 3. And Proposition ensures that the incumbent will not deviate in either introduction time or R&D project. Since neither the entrant nor the incumbent will deviate from (D, D), we conclude that (D, D) is a Nash equilibrium. Combining all three Nash equilibrium candidates, we establish the following proposition:

**Proposition 5.** There is a unique Nash equilibrium in pure strategy in which the entrant will move first by introducing a drastically improved new product at  $t_{2,1st}^{(D,D)}$ , given by (10), and the incumbent will respond by introducing a drastically improved new product at  $t_1^{(D,D)}$ , given by (9).

#### 4. The Sequential Game

In this section, we study the situation where the incumbent does not anticipate the entrant's move, either due to its ignorance of the entrant or its myopic behavior. In this case, the entrant first enters the market, and then the incumbent, upon observing the entrant's move, initiates an R&D project in reaction to the entry. We use backward induction by analyzing the incumbent's reaction first. First, consider an entrant who introduces an incrementally improved product.

Entry with an incrementally improved product. Suppose the entrant introduces an incrementally improved product at time  $T_2$ . At time  $T_2$ , the incumbent can start its R&D project in reaction to the entry. If the incumbent decides to complete its R&D project in time  $t_1$ , it can introduce its new product at  $T_1 = T_2 + t_1$ . Suppose the incumbent's reaction is to introduce an

incrementally improved new product at  $T_1 = T_2 + t_1$ . Then the incumbent's profit discounted back to  $T_2$  is<sup>11</sup>

$$\Pi_{1}^{(I,I)} = \frac{1}{\delta} \frac{1}{1+I} + \frac{1}{\delta} \frac{I^{2}}{(1+I)(1+2I)} e^{-\delta_{1}} - \frac{\delta I^{2}}{e^{\delta_{1}} - 1}$$

and its discounted profit is maximized at  $t_1 = t_1^{(I,I)}$ , given by (6). If the incumbent decides to react by introducing a drastically improved new product at  $T_1 = T_2 + t_1$ , its profit discounted back to  $T_2$  is

$$\Pi_{1}^{(D,I)} = \frac{1}{\delta} \frac{1}{1+I} + \frac{1}{\delta} \frac{ID}{(1+I)(1+I+D)} e^{-\delta_{1}} - \frac{\delta D^{2}}{e^{\delta_{1}} - 1},$$

and its disounted profit is maximized at  $t_1 = t_1^{(D,I)}$ , given by (7), if condition (8) is satisfied; otherwise the incumbent will not introduce a drastically improved new product. Using the results in subsection 3.1, we can summarize the following lemma:

**Lemma 1.** In reaction to the entrant's strategy of  $\{I, T_2\}$ , the incumbent will introduce a drastically improved new product at  $T_1 = T_2 + t_1^{(D,I)}$  if condition (8) is satisfied, otherwise, it will introduce an incrementally improved new product at  $T_1 = T_2 + t_1^{(I,I)}$ .

Working backward, we can derive the entrant's optimal entry strategy  $\{I, T_2\}$ .

**Entry with a drastically improved product**. According to Proposition 2, the incumbent will always react with the drastic R&D project, so we have

<sup>&</sup>lt;sup>11</sup> We do not discount the incumbent's profit back to time 0 because its profit prior to  $T_2$  is not affected by its R&D strategy.

**Lemma 2.** In reaction to the entrant's strategy of  $\{D, T_2\}$ , the incumbent will introduce a drastically improved new product at  $T_1 = T_2 + t_1^{(D,D)}$ .

Again, by working backward, we can derive the entrant's optimal strategy  $\{D, T_2\}$ .

To determine the entrant's strategy in equilibrium, we compare  $\{I, T_2\}$  and  $\{D, T_2\}$  and conclude that, (the proof is similar to that of Proposition 5):

**Proposition 6.** In the sequential game where the entrant moves first and the incumbent starts its R&D project only upon observing the entry, there is a unique Nash equilibrium in pure strategy in which the entrant will introduce a drastically improved product at

$$T_{2}^{(D,D)} = -\frac{1}{\delta} \ln \left[ 1 - \delta D / \sqrt{\frac{D}{1+D} \left[ 1 - \frac{D\left(1 - \delta \sqrt{(1+D)(1+2D)}\right)}{1+2D} \right]} \right],$$

and the incumbent reacts by introducing a drastically improved new product at  $T_1^{(D,D)} = T_2^{(D,D)} + t_1^{(D,D)}.$ 

We first note that, although the incumbent does not anticipate entry in the sequential game, this does not mean that the incumbent will panic and try to expedite its R&D project, as illustrated by the following corollary:

**Corollary 1.** The actual time to complete the R&D project for the incumbent in the sequential game is  $t_1^{(D,D)}$ , the same as in the simultaneous game.

However, the entrant can take advantage of the incumbent's ignorance. Comparing with the simultaneous game, we can establish the following corollary:

**Corollary 2**. In the sequential game, the entrant will accelerate its entry to  $T_2^{(D,D)}$  from  $t_{2,lst}^{(D,D)}$  because  $t_{2,lst}^{(D,D)} > T_2^{(D,D)}$ . Further, the entrant is better off and the incumbent is worse off in the sequential game than in the simultaneous game.

The above result can be understood by considering the entrant's profit rates. The entrant enjoys a profit rate of D/(1+D) before the incumbent can react to its entry and a reduced profit rate of D/(1+2D) after the incumbent's reaction. In the simultaneous game, the entrant enjoys the higher profit rate for a period of  $t_1^{(D,D)} - t_{2,1st}^{(D,D)}$ , and in the sequential game, for a period of  $t_1^{(D,D)}$ . Thus, with a longer period of time to enjoy the higher profit rate and because the future profit is discounted, it is more advantageous for the entrant to accelerate its entry in the sequential game, resulting in an overall increased profit.

#### 5. Discussions and Conclusions

This paper studies the entrant's and the incumbent's R&D strategies in a setting of rivalrous competition. The focus of our inquiry was on three decisions that consist of a firm's R&D strategy: investment in an R&D project, product performance improvement, and the introduction time. Our analysis recognizes that (i) these three decisions need to be made jointly, and (ii) that they need to be made by taking into account the competitor's similar decisions.

The key finding of the model is that, when entering a market, regardless of whether the incumbent anticipates its entry intention or not, the entrant should always introduce a product that will leapfrog the incumbent's current product in performance, even if this means that it will cost more to develop such a product and the introduction has to be delayed. When it is aware of the entrant's intention to enter the market, the incumbent, in response to the entrant's strategy,

should develop a new product whose performance is drastically improved from the existing product. Incremental improvement contributes little to shield the incumbent's leadership position from the entrant' threats, and it is not sufficient for the entrant to challenge the incumbent's position. Returning to the example of Microsoft, the company, in its race with Netscape Communications in the market of Internet browsers, did not achieve much success as measured by market share by releasing four successive versions of Internet Explorer in little more than a year. Microsoft would have been able to save R&D costs and achieve better results had it invested in just one much improved version, perhaps at the expense of a delayed introduction. Note that this is the strategy Microsoft adopted when introducing Windows 95 operating system with much success.

The model also shows that it is not necessary for the incumbent to preempt the entrant's entry by releasing its next generation product ahead of entry. This is essentially a trade-off between prompt reaction to entry and the cost of accelerating new product introduction. Rushing to the market, particularly with a drastically improved product proves to be too costly for the incumbent.

When the incumbent is not aware of the entrant's existence, it cannot start its R&D project in reaction to the entry until the entry occurs. In this case, the entrant's strategy will be different. Since it will take longer for the incumbent to introduce a new product in reaction to the entry, the entrant can enjoy the higher profit rate for a longer period of time. Thus, the entrant should expedite its R&D project so it can enter the market earlier. The incumbent, although caught off guard due to its failure to anticipate the entry, should not move too hastily in reaction to the entry. Rather, it should proceed with its R&D project at the same rate as in the simultaneous game. This result is consistent in spirit with the entrant's strategy in that one

should always take time to improve the product drastically rather than rushing to the market prematurely. This finding is consistent with Bayus, Jain, and Rao (1997) in their conclusion that Apple Computer's Newton is "too little, too early."<sup>12</sup>

Our findings contribute to three major debates regarding a firm's R&D strategy: the incumbent's choice between a radical R&D project and an incremental one, the incumbent's decision of whether to pre-empt the entrant, and the trade-off between product quality improvement and time-to-market. Our findings show that the incumbent should introduce a radically improved new product. Furthermore, the entrant should adopt a similar R&D strategy. We also show that the incumbent should not pre-empt the entrant in the R&D race. We further show that both the incumbent and the entrant should emphasize product quality improvement over time-to-market.

Our model is most appropriate for those R&D situations where the firm has control over its R&D project in terms of completion time and product quality improvement. Our model is not appropriate for situations where the successful completion of the R&D project at a predetermined time is uncertain such as the development of a drug. It is also not appropriate for the winner-take-all situation due to either patent protection or other barriers. Our model needs to be modified if there is a strong network externality effect (Dhebar and Oren 1985) on consumers' choice behavior. In this case, not only do consumers consider product quality when making choices, but also take into account the installed base of each technology and the compatibility of the two technologies because these factors will affect utilities consumers can derive from the

<sup>&</sup>lt;sup>12</sup> Actually, Apple's R&D strategy with Newton was to rush to the market with a radical innovation, the handwriting recognition technology. As shown in this paper, this strategy is clearly not optimal in the Nash equilibrium.

products. An early entry may be more important than the product performance to the entrant in the presence of network externality effect, resulting in a Nash equilibrium different from (D,D).

#### Appendix

#### A. R&D cost minimization

Let  $Y(t) = \int_0^t y(s) ds$ ,  $0 \le t \le T$ . Now the problem can be rewritten as

$$\min_{Y(t)} \int_{0}^{T} e^{-\delta t} (Y'(t))^{2} dt,$$
s.t.  $Y(0) = 0, \ Y(T) = \Delta v, \ Y'(t) \ge 0 \ \forall t \in [0, T].$ 
(A1)

Let  $F(t, Y(t), Y'(t)) = e^{-\delta t} Y'^2(t)$ , then

$$\frac{\partial F}{\partial Y(t)} = 0, \quad \frac{\partial F}{\partial Y'(t)} = 2e^{-\delta t}Y'(t).$$

The Euler equation is  $0 = \frac{d}{dt} \left[ 2e^{-\delta t} Y'(t) \right]$ . After simplification, it becomes  $Y''(t) - \delta Y'(t) = 0$ .

This is a second order differential equation, which can be solved to yield

$$Y(t) = k_1 \frac{e^{\delta t}}{\delta} k_2$$

Boundary conditions

$$Y(0) = 0 = \frac{k_1}{\delta} + k_2$$
 and  $Y(T) = \Delta v = k_1 \frac{e^{\delta T}}{\delta} + k_2$ 

give the values for the constants of integration

$$k_1 = \frac{\delta \Delta v}{e^{\delta T} - 1}, \ k_2 = -\frac{\Delta v}{e^{\delta T} - 1}.$$

Hence, the solution to problem (A1) is

$$Y(t) = \Delta v \frac{e^{\delta t} - 1}{e^{\delta T} - 1}$$
 and  $y(t) = \frac{\delta \Delta v}{e^{\delta T} - 1} e^{\delta t}$ .

#### **B.** Regularity Condition (5)

If the entrant knows that the incumbent will not react to its entry, then its discounted profit with an incrementally improved product is

$$\Pi_{2}(\{I,t_{2}\}|\{0,t_{1}\}) = \int_{t_{2}}^{\infty} \pi(I|1)e^{-\delta t}dt - C(I,t_{2}) = \frac{Ie^{-\delta t_{2}}}{\delta(1+I)} - \frac{\delta I^{2}}{e^{\delta t_{2}} - 1}$$

Then, the entrant can maximize its discounted profit at  $t_2^*(I) = -\frac{1}{\delta} \ln \left[1 - \delta \sqrt{I(1+I)}\right]$  and the

maximized profit is  $\Pi_2^*(I) = \frac{I\left[1 - \sqrt{I(1+I)}\right]^2}{\delta(1+I)}$ . Similarly, if the entrant introduces a drastically

improved product, its optimal entry time is  $t_2^*(D) = -\frac{1}{\delta} \ln \left[1 - \delta \sqrt{D(1+D)}\right]$  and its maximized

profit is  $\Pi_2^*(D) = \frac{D[1 - \sqrt{D(1+D)}]^2}{\delta(1+D)}$ . The entrant will enter the market if  $t_2^*(I)$  and/or  $t_2^*(D)$  are

positive, which is true if

$$\delta < \frac{1}{\sqrt{D(1+D)}}.\tag{B1}$$

Note that (B1) is a necessary condition for the entrant to enter the market with a drastically improved product. Even if (B1) holds, the entrant may still introduce an incrementally improved product if  $\Pi_2^*(I) > \Pi_2^*(D)$ .

#### C. The incumbent's potential reactions

**Proof of Proposition 1.** Suppose (8) holds. In reaction to the entrant's  $\{I, t_2\}$ , the incumbent's reactions and corresponding profits are summarized in Table C1. With  $t_1^{(I,I)} < t_1^{(D,I)}$ , we consider three intervals of  $t_2 : [0, t_1^{(I,I)}], (t_1^{(I,I)}, t_1^{(D,I)}], and (t_1^{(D,I)}, \infty)$ . In the

first interval, according to Table C1, we can establish that, between  $\{I, t_1^{(I,I)}\}$  and  $\{D, t_1^{(D,I)}\}$ , the incumbent is better off with the latter if

$$\delta < \frac{\sqrt{\frac{D(1+2I)}{I(1+I+D)}} - 1}{\left(\frac{D}{I} - 1\right)\sqrt{(1+I)(1+2I)}},$$

which is true due to (8).

#### [Table C1 about here]

In the second interval, between  $\{I, t_2\}$  and  $\{D, t_1^{(D,I)}\}$ , the incumbent will prefer the latter if

$$\Psi = \left[\frac{ID\left(1 - \delta\sqrt{\frac{D(1+I)(1+I+D)}{I}}\right)^2}{(1+I)(1+I+D)} - \frac{I}{1+I}e^{-\tilde{\alpha}_2}\right] - \left[-\frac{I}{1+2I}e^{-\tilde{\alpha}_2} - \frac{(\delta I)^2}{e^{\tilde{\alpha}_2} - 1}\right] > 0$$

Note that  $\frac{1}{(1+I)(1+2I)}e^{-\delta t_2} - \frac{\delta^2}{e^{\delta t_2}-1}$  is decreasing in  $t_2$  for  $t_2 > t_1^{(I,I)}$ , we have

$$\begin{split} \Psi &> \frac{ID\!\!\left(1 - \delta\sqrt{\frac{D\!\!\left(1 + I\right)\!\!\left(1 + I + D\right)}{I}}\right)^2}{(1 + I)\!\!\left(1 + I + D\right)} - I^2\!\!\left[\frac{1}{(1 + I)\!\!\left(1 + 2I\right)}e^{-\delta\!\!\left[^{I,I}\right]} - \frac{\delta^2}{e^{-\delta\!\!\left[^{I,I}\right]} - 1}\right]}{\frac{ID\!\!\left(1 - \delta\sqrt{\frac{D\!\!\left(1 + I\right)\!\!\left(1 + I + D\right)}{I}}\right)^2}{(1 + I)\!\!\left(1 + I + D\right)} - \frac{I^2\!\!\left[1 - \delta\sqrt{(1 + I)\!\!\left(1 + 2I\right)}\right]}{(1 + I)\!\!\left(1 + 2I\right)} > 0, \end{split}$$

confirming that the incumbent will choose  $\left\{D, t_1^{(D,I)}\right\}$ .

In the third interval, the incumbent's profit with  $\{D, t_2\}$  will be greater than with  $\{I, t_2\}$  if

$$\Theta = \left(-\frac{I}{1+I+D}e^{-\tilde{\alpha}_2} - \frac{(\delta D)^2}{e^{\tilde{\alpha}_2} - 1}\right) - \left(-\frac{I}{1+2I}e^{-\tilde{\alpha}_2} - \frac{(\delta I)^2}{e^{\tilde{\alpha}_2} - 1}\right) > 0^{\frac{1}{2}}$$

which is true if

$$\delta < \frac{1}{(I+D)(1+2I)} \sqrt{\frac{ID(1+I)}{1+I+D}}$$

The above condition holds due to (8), confirming that the incumbent will choose  $\{D, t_2\}$ .

Combining all three intervals, we show that the incumbent always prefers D to I for small I.

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**Proof of Proposition 2.** The incumbent's maximized profits in reaction to the entrant's strategy of  $\{D, t_2\}$  are summarized in Table C2. Similar to Proposition 1, we consider three intervals for  $t_2 : \left[0, t_1^{(I,D)}\right], \left(t_1^{(I,D)}, t_1^{(D,D)}\right]$ , and  $\left(t_1^{(D,D)}, \infty\right)$ . Following the proof of Proposition 1 and using the incumbent's profits in Table C2, we can prove that the incumbent will always choose *D* in reaction to the entrant's strategy of  $\{D, t_2\}$ .

#### [Table C2 about here]

### **D.** Entrant's deviation from (I,I)

With the Nash equilibrium candidate (I, I), if the entrant deviates to D, its profit is

$$\Pi_{2,dev}^{(I,D)} = \frac{1}{\delta} \frac{D}{1+I+D} \Big[ 1 - \delta \sqrt{D(1+I+D)} \Big]^2.$$

Note that (I,I) is a Nash equilibrium candidate only if  $I < \hat{I}$ , where  $\hat{I}$  is determined by (8). With  $\hat{I}$  decreasing in D, we have  $I < \hat{I} \le \hat{I}|_{D=1} = 0.069$ . Thus, I is a much smaller number than D. Hence, we have

$$\Pi_{2,dev}^{(I,D)} \approx \frac{1}{\delta} \frac{D}{1+D} \Big[ 1 - \delta \sqrt{D(1+D)} \Big]^2 > \frac{1}{\delta} \frac{D}{1+D} \Big[ 1 - \frac{1}{2(1+D)} \Big]^2,$$

and using the regularity condition (5), we have  $\Pi_{2,dev}^{(I,D)} > 0.28 / \delta$ . Using Table 3, we further have

$$\Pi_{2}^{(I,I)} < \frac{1}{\delta} \frac{I \Big[ 1 - \delta \sqrt{I(1+I)} \Big]^2}{1+I} < \frac{1}{\delta} \frac{I}{1+I} < 0.065 / \delta \,.$$

Hence,  $\Pi_2^{(I,I)} < \Pi_{2,dev}^{(I,D)}$ .

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R&D*	Incumbent pre-empts entry	Incumbent does not pre-empt entry
(I,I)	$\frac{1}{\delta} - \frac{1}{\delta} \frac{I}{1+2I} e^{-\delta t_2} - \frac{\delta I^2}{e^{\delta t_1} - 1}$	$\frac{1}{\delta} + \frac{1}{\delta} \frac{I^2}{(1+I)(1+2I)} e^{-\delta_1} - \frac{1}{\delta} \frac{I}{1+I} e^{-\delta_2} - \frac{\delta I^2}{e^{\delta_1} - 1}$
(I,D)	$\frac{1}{\delta} - \frac{1}{\delta} \frac{D}{1+I+D} e^{-\delta t_2} - \frac{\delta I^2}{e^{\delta t_1} - 1}$	$\frac{1}{\delta} + \frac{1}{\delta} \frac{ID}{(1+D)(1+I+D)} e^{-\delta t_1} - \frac{1}{\delta} \frac{D}{1+D} e^{-\delta t_2} - \frac{\delta I^2}{e^{\delta t_1} - 1}$
(D,I)	$\frac{1}{\delta} - \frac{1}{\delta} \frac{I}{1+I+D} e^{-\delta t_2} - \frac{\delta D^2}{e^{\delta t_1} - 1}$	$\frac{1}{\delta} + \frac{1}{\delta} \frac{ID}{(1+I)(1+I+D)} e^{-\delta_1} - \frac{1}{\delta} \frac{I}{1+I} e^{-\delta_2} - \frac{\delta D^2}{e^{\delta_1} - 1}$
(D,D)	$\frac{1}{\delta} - \frac{1}{\delta} \frac{D}{1+2D} e^{-\delta t_2} - \frac{\delta D^2}{e^{\delta t_1} - 1}$	$\frac{1}{\delta} + \frac{1}{\delta} \frac{D^2}{(1+D)(1+2D)} e^{-\delta t_1} - \frac{1}{\delta} \frac{D}{1+D} e^{-\delta t_2} - \frac{\delta D^2}{e^{\delta t_1} - 1}$

Table 1 The Incumbent's Profits under Different Scenarios

\* First letter indicates the incumbent's choice of R&D project, and the second letter the entrant's.

R&D*	Entrant moves first	Entrant moves second
(I,I)	$\frac{1}{\delta}\frac{I}{1+I}e^{-\delta t_2} - \frac{1}{\delta}\frac{I^2}{(1+I)(1+2I)}e^{-\delta t_1} - \frac{\delta I^2}{e^{\delta t_2} - 1}$	$\frac{1}{\delta} \frac{I}{1+2I} e^{-\delta t_2} - \frac{\delta I^2}{e^{\delta t_2} - 1}$
(I,D)	$\frac{1}{\delta} \frac{D}{1+D} e^{-\delta t_2} - \frac{1}{\delta} \frac{ID}{(1+D)(1+I+D)} e^{-\delta t_1} - \frac{\delta D^2}{e^{\delta t_2} - 1}$	$\frac{1}{\delta} \frac{D}{1+I+D} e^{-\delta t_2} - \frac{\delta D^2}{e^{\delta t_2} - 1}$
(D,I)	$\frac{1}{\delta}\frac{I}{1+I}e^{-\delta t_2} - \frac{1}{\delta}\frac{ID}{(1+I)(1+I+D)}e^{-\delta t_1} - \frac{\delta I^2}{e^{\delta t_2} - 1}$	$\frac{1}{\delta} \frac{I}{1+I+D} e^{-\delta t_2} - \frac{\delta I^2}{e^{\delta t_2} - 1}$
$(D,\overline{D})$	$\frac{1}{\delta}\frac{D}{1+D}e^{-\delta t_2} - \frac{1}{\delta}\frac{D^2}{(1+D)(1+2D)}e^{-\delta t_1} - \frac{\delta D^2}{e^{\delta t_2} - 1}$	$\frac{1}{\delta} \frac{D}{1+2D} e^{-\delta t_2} - \frac{\delta D^2}{e^{\delta t_2} - 1}$

Table 2 The Entrant's Profits under Different Scenarios

\* First letter indicates the incumbent's choice of R&D project, and the second letter the entrant's.

R&D	Incumbent's Profit	Entrant's Profit
(I,I)	$\frac{1}{\delta} + \frac{1}{\delta} \frac{I^2 \left(1 - \delta \sqrt{(1+I)(1+2I)}\right)^2}{(1+I)(1+2I)} - \frac{1}{\delta} \frac{I \left(1 - \delta \sqrt{I(1+I)}\right)}{1+I}$	$\frac{1}{\delta} \frac{I(1 - \delta\sqrt{I(1+I)})^2}{1+I} - \frac{1}{\delta} \frac{I^2(1 - \delta\sqrt{(1+I)(1+2I)})}{(1+I)(1+2I)}$
(D,I)	$\frac{1}{\delta} + \frac{1}{\delta} \frac{ID\left(1 - \delta\sqrt{\frac{D(1+I)(1+I+D)}{I}}\right)^2}{(1+I)(1+I+D)} - \frac{1}{\delta} \frac{I\left(1 - \delta\sqrt{I(1+I)}\right)}{1+I}$	$\frac{1}{\delta} \frac{I(1-\delta\sqrt{I(1+I)})^2}{1+I} - \frac{1}{\delta} \frac{ID\left(1-\delta\sqrt{\frac{D}{I}(1+I)(1+I+D)}\right)}{(1+I)(1+I+D)}$
(D,D)	$\frac{1}{\delta} + \frac{1}{\delta} \frac{D^2 \left(1 - \delta \sqrt{(1+D)(1+2D)}\right)^2}{(1+D)(1+2D)} - \frac{1}{\delta} \frac{D \left(1 - \delta \sqrt{D(1+D)}\right)}{1+D}$	$\frac{1}{\delta} \frac{D(1 - \delta\sqrt{D(1+D)})^2}{1+D} - \frac{1}{\delta} \frac{D^2(1 - \delta\sqrt{(1+D)(1+2D)})}{(1+D)(1+2D)}$

Table 3 Two Firms' Profits in Three Equilibrium Candidates

Table C1 The Incumbent's Reactions to the Entrant's Strategy of  $\{I, t_2\}$ 

R&D	$t_2$	Introduction Time	Incumbent's Maximized Profit
(I,I)	$\left[0,t_1^{(I,I)}\right]$	$t_1^{(I,I)}$	$\frac{1}{\delta} + \frac{1}{\delta} \frac{I^2 \left(1 - \delta \sqrt{(1+I)(1+2I)}\right)^2}{(1+I)(1+2I)} - \frac{1}{\delta} \frac{I}{1+I} e^{-\delta_2}$
(I,I)	$\left(t_{1}^{\left(I,I\right)},\infty\right]$	<i>t</i> <sub>2</sub>	$\frac{1}{\delta} - \frac{1}{\delta} \frac{I}{1+2I} e^{-\tilde{\alpha}_2} - \frac{\delta I^2}{e^{\tilde{\alpha}_2} - 1}$
(D,I)	$\left[0,t_1^{(D,I)}\right]$	$t_1^{(D,I)}$	$\frac{1}{\delta} + \frac{1}{\delta} \frac{ID\left(1 - \delta\sqrt{\frac{D(1+I)(1+I+D)}{I}}\right)^2}{(1+I)(1+I+D)} - \frac{1}{\delta} \frac{I}{1+I} e^{-\delta_2}$
(D,I)	$\left(t_1^{(D,I)},\infty\right)$	<i>t</i> <sub>2</sub>	$\frac{1}{\delta} - \frac{1}{\delta} \frac{I}{1+I+D} e^{-\tilde{\alpha}_2} - \frac{\delta D^2}{e^{\tilde{\alpha}_2} - 1}$

R&D	$t_2$	Introduction Time	Incumbent's Maximized Profit
(I,D)	$\left[0,t_1^{(I,D)}\right]$	$t_1^{(I,D)}$	$\frac{1}{\delta} + \frac{1}{\delta} \frac{ID\left(1 - \delta\sqrt{\frac{I(1+D)(1+I+D)}{D}}\right)^2}{(1+D)(1+I+D)} - \frac{1}{\delta} \frac{D}{1+D} e^{-\tilde{\alpha}_2}$
(I,D)	$\left(t_{1}^{\left(I,D\right)},\infty\right]$	<i>t</i> <sub>2</sub>	$\frac{1}{\delta} - \frac{1}{\delta} \frac{D}{1+I+D} e^{-\tilde{\alpha}_2} - \frac{\delta I^2}{e^{\tilde{\alpha}_2} - 1}$
(D,D)	$\left[0,t_1^{(D,D)}\right]$	$t_1^{(D,D)}$	$\frac{1}{\delta} + \frac{1}{\delta} \frac{D^2 \left(1 - \delta \sqrt{(1+D)(1+2D)}\right)^2}{(1+D)(1+2D)} - \frac{1}{\delta} \frac{D}{1+D} e^{-\delta_2}$
(D,D)	$\left(t_1^{(D,D)},\infty\right)$	<i>t</i> <sub>2</sub>	$\frac{1}{\delta} - \frac{1}{\delta} \frac{D}{1+2D} e^{-\vartheta_2} - \frac{\delta D^2}{e^{\vartheta_2} - 1}$

Table C2 The Incumbent's Reactions and Profits to the Entrant's Strategy of  $\{D, t_2\}$ 



Figure 1 Gross Profit Margins for Selected High-Technology Firms







