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Some firms, particularly in high-tech, appear to view technology leadership and cost leadership as separate and distinct ways of achieving high profits within a given product market. In contrast, we develop a model of technology competition suggesting that a firm's success in sustaining its technology leadership may hinge on its ability to produce the new product (resulting from the new technology) at lower cost, an ability we call the firm's "cost competence." In our model, cost competence, above a critical hurdle level, is essential to the incumbent firm in its bid to retain technology leadership. The model also clarifies the role of "innovative competence," which characterizes a firm's ability to turn an investment in new technology into a marketable product. We present an example of a standard product market model (for determining prices and production quantities for two competing products in the aftermath of the technology competition) in which the assumptions of our technology competition model hold.

An additional key finding is that there can be discontinuities in the returns that accrue from enhanced cost competence. If a firm is on the right side of a "jump point," its expected profits can be dramatically more than if it were only slightly less competent. These jump points arise where the firm's cost competence becomes sufficient to cause a competitor to decide against competing in the new technology, or to significantly drop its investment amount. When a potential competitor backs down, the prospect of high returns for the incumbent opens up.
(*Manufacturing Strategy; Cost Competence; Product Innovation; Process Innovation; Technological Change; Technology Leadership*)

1. Introduction

High-tech companies typically focus on continual and rapid product changes, incorporating the latest exogenous developments in technology. This emphasis on innovation sometimes appears to be accompanied by a *reduced* emphasis on production cost. For example, the CEO of a computer workstation manufacturer has stated:

> (Other companies) strive to be the leader in low costs rather than in innovation. . . . . Our philosophy is that the key to achieving competitive advantage . . . . is being an innovation leader (Prokesch 1993, p. 135).

The implication is that a firm should either differentiate itself by being a cost leader, or it should differentiate itself by being an innovation leader: To focus on cost in a high-tech environment may seem at best irrelevant, and at worst counterproductive. Aggressively pursuing cost reduction might suggest that the firm has resigned itself to competing on price, rather than on developing new leading-edge products.

This paper challenges that general viewpoint. In our

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model of technology competition, where there is the opportunity for a new product, cost competence is the firm's ability to produce that *new* product at lower cost than a potential competitor. And, in our model, to insure technology leadership, cost competence is essential, rather than irrelevant! Thus, we do not address the issue of whether a firm should differentiate itself as a "cost leader" by offering a lower-cost, lower-featured product, versus offering a technologically advanced higher-cost product. Rather, we are simply asking what is required for a firm who is a technology leader (a firm achieving above-market returns with a technologically advanced product) to maintain that status in the face of a potential competitor. Furthermore, our model does not explicitly address the problem of what competencies a firm should develop and to what levels they should be developed, but provides building blocks for such an analysis. In particular, we take cost competence and what we call innovative competence as given abilities of the competing firms and analyze the competitive consequences.

Our definition of cost competence may represent a broadened view of cost leadership to such a technology leader. In addition to evaluating a cost initiative on the basis of how it affects the *current* product, this firm may need to assess more broadly its implications on the *next* generation of product. If a cost advantage the firm achieves today can (to some extent) carry over to the new product generation, the impact of this cost initiative will continue when a new technology arises.

Furthermore, a technology leader may have a strategic incentive to pursue cost competence: By demonstrating its ability to achieve a low cost position, the firm may alter the competitor's decision to invest in a new technology. Changing the competitive landscape in this fashion can raise contribution margins not only because the firm has lowered its own cost, but also because it is able to achieve a higher margin during the (possibly short) lifetime of the product.

This is not to suggest that a technology leader should ignore or diminish its emphasis on innovation. The model presented herein also identifies the role of "innovative competence," which characterizes the firm's likelihood of mastering a new technology, as a function of its investment level.

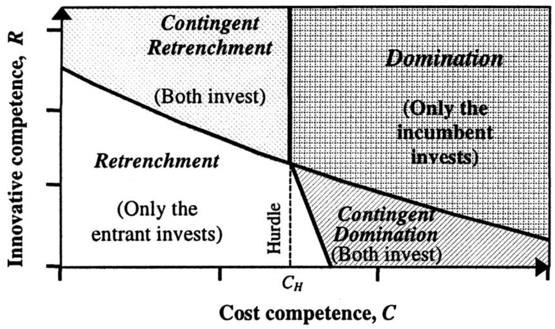
Both cost competence and innovative competence are found to play critical roles in assuring that the firm continues to invest in appropriate new technologies. However, we highlight the role of cost competence because it may be less intuitive as to how this ability contributes to technology leadership. (It appears more straightforward to conclude that innovative competence contributes to technology leadership, although hopefully this work also generates some new insights regarding the exact contribution that innovative competence makes.) Another reason for highlighting the role of cost competence is that a core objective of the Operations Management (OM) field is to help firms reduce cost. Inventory management, capacity management, supply chain management, flexible manufacturing, and shop floor control are factors that help establish a firm's cost competence.

A synopsis of our technology competition model follows. An incumbent is a technology leader with an existing (old) product, holding a monopoly position. Both the incumbent and a new entrant firm have one opportunity (each) to invest in an uncertain new technology. The relative competence levels of the firms determine investment amounts, which, in turn, determine the firms' probabilities of successfully developing a viable new technologically advanced product. A successful firm has the option of marketing the new product that competes with the incumbent's old product (and the competitor's new product, if both firms are successful).

The paper generally takes the perspective of the incumbent, who is trying to sustain her technology leadership position. We present conditions under which the incumbent faces a "competence map" of the type shown in Figure 1. (Theorem 2, in §3, reveals how the exact shape and scale of the map depend upon the specific parameters of the problem.) Depending on her innovative and cost competence levels (denoted as R and C, respectively), the incumbent finds herself in one of four regions.

With relatively *low* levels of each competence, the incumbent finds herself in the retrenchment region: She retrenches with the old technology and only the entrant invests in the new technology. Her only hope for retaining technology leadership is that the entrant fails to master the new technology. With relatively *high* levels of each competence, she is in the domination

Figure 1 **A Firm's Status is Established by Its Position on Its Competence Map**



region: Her firm dominates, venturing ahead on its own in pursuit of the new technology. She is so formidable that the competitor cannot see any benefit from concurrently investing in the new technology. Essentially, she "forces" a competitor to look elsewhere for an attractive investment opportunity. She is assured of retaining technology leadership, either with the old product if she fails to master the new technology, or with both the new and old products if she succeeds.

Two other regions, the contingent retrenchment and contingent domination zones, are characterized by investments by both firms. However, as shown in a later illustration (Figure 3), the contingent retrenchment region may offer an expected profit only marginally higher than that of the retrenchment region, while the contingent domination zone may offer an expected profit that approaches that of the domination zone. Within the contingent domination region, our illustration shows a steep rise in expected profit with increasing levels of either competence.

Theorem 3, given in §3, shows that the boundary between the contingent retrenchment and domination regions represents a "jump point" as described in the abstract. A slightly higher level of cost competence offers a discontinuous jump in expected profit. We later illustrate this with an example in Figure 3, where the incumbent can achieve dramatic expected returns only if she is in either the domination or contingent domination regions.

Cost competence is thus a critical element in the firm's positioning, perhaps even more significant than innovative competence. Unless the incumbent's cost competence exceeds a critical "hurdle" level C_H, she cannot be in the domination or contingent domination regions and therefore cannot achieve dramatic expected returns. In particular, if the incumbent would not be able to produce the next product more cheaply than its competitor, she is doomed to relatively low expected returns.

Section 2 develops the generic model of technology competition. Section 3 gives our main results. Section 4 presents an example of a supporting model of market competition, which defines the firms' profits in the aftermath of the technology competition. It satisfies the assumptions of our theorems and is used to illustrate the impact of cost competence. Section 5 positions this work within the broad spectrum of literature that surrounds our research question. Section 6 discusses results and outlines potential future work. Appendix 1 offers a summary of notation used in the paper.

2. Model of Technology Competition

The incumbent monopolist (the technology leader) and a potential entrant must decide how much, if any, to invest in an uncertain new technology. A firm that invests takes the risk that it can develop a viable new product based on the new technology. If successful, a firm has the opportunity to market the new product alongside the incumbent's existing (old) product. In other words, success with a *new technology* leads to a *new product*, and therefore these terms are used interchangeably.

As indicated earlier, there are two distinct competence levels that will be pertinent to the model, which are now formally defined. *Cost competence, C,* is the incumbent's percent cost advantage in producing the new product, measured relative to the entrant's production cost. Specifically, let c_I and c_E denote the incumbent's and entrant's costs for the new product, respectively (subscripts "I" and "E" will be used to denote parameters associated with the incumbent and entrant, respectively). Thus, $C \equiv 100\,(c_E - c_I)/c_E$.

Innovative competence, R, describes the incumbent's relative advantage in being able to achieve success from a given investment, and will be defined precisely below. Let K_I and K_E denote the investments of the incumbent and entrant, respectively, and let $P_I(K_I)$ and $P_E(K_E)$ denote their respective resulting probabilities of success. We assume an exponential relationship:

$$P_I(K_I) = 1 - \exp(-r_I K_I), \quad \text{where } r_I > 0, \tag{1}$$

$$P_E(K_E) = 1 - \exp(-r_E K_E), \quad \text{where } r_E > 0. \tag{2}$$

For example, for every additional unit the incumbent invests in the project, the reduction in the probability of failure is equal to the current failure probability multiplied by $1 - \exp(-r_I)$: When r_I is small, this multiplier is approximately r_I. That is, if the units of investment are \$1000s and $r_I = 0.03$, and an additional \$1000 is invested in the project, then the probability of failure becomes 97% of its previous value, reflecting the 3% reduction. Thus, higher investment levels lead to diminishing returns.

Mansfield and Brandenburg (1966) used a similar relationship in modeling the firm's choice of R&D investments. They found statistically significant empirical support for this formulation, based on a sample of eleven major projects.

The parameters r_I and r_E represent investment effectiveness. The incumbent's innovative competence, R, is formally defined as the ratio of the firms' investment effectiveness parameters: $R \equiv r_I/r_E$. If $R > 1$, then the incumbent achieves a higher probability of success for the same investment amount.

This is a one-period model in that there is only one chance to invest. However, the period consists of three stages: 1) The firms simultaneously decide how much to invest; 2) The firms either succeed or fail, with the outcomes becoming common knowledge; and 3) The firms realize their profits. If only the incumbent succeeds in stage two, the incumbent's and entrant's gross profits in stage three, exclusive of investment cost, are denoted by $\pi_I^{SF}(C)$ and π_E^{SF}, respectively. The subscript refers to the firm, the first superscript to the incumbent's outcome, success (S) or failure (F), and the second superscript to the entrant's outcome. Failure can occur with or without investment. The profits under the other outcomes are indicated analogously. Note that gross profit amounts associated with the incumbent's success (except π_E^{SF}) can depend strongly on C, the incumbent's cost competence, because each firm's relative costs will influence the returns to each firm (these are shown as functions C, while the others are independent of C). However, these amounts are independent of R, the incumbent's innovative competence. (R plays a role in determining whether the firm succeeds or fails, but does not impact the firm's profit given its success or failure.)

Note that this model of technology competition is generic in that it will accommodate various types of supporting models to determine the eight profit numbers. We make several basic assumptions regarding the game itself, as given in Assumptions (A1) through (A5) below. We make several additional assumptions, given in Assumptions (A6) through (A8), related to the supporting model. (Assumptions are in italics, followed possibly by interpretations.)

Assumption (A1). *Both the incumbent and the entrant are aware of their own and their competitor's costs, potential profits, and investment effectiveness parameters r_I and r_E.*

Assumption (A2). *Firms are risk neutral: Each seeks an option that will maximize its expected net profit.*

Assumption (A3). *The entrant does not implement the old technology.*

Assumption (A4). *When successful but indifferent about implementing the new technology, a firm will choose to implement it.*

Assumption (A5). $\pi_E^{SF} = \pi_E^{FF} = 0$: If the entrant fails, he receives no gross profit.

Assumption (A6). $0 \le \pi_{\mathrm{I}}^{\mathrm{SS}}(C) \le \pi_{\mathrm{I}}^{\mathrm{SF}}(C)$, $0 \le \pi_{\mathrm{I}}^{\mathrm{FS}} \le \pi_{\mathrm{I}}^{\mathrm{FF}}$, $0 \le \pi_{\mathrm{E}}^{\mathrm{SS}}(C) \le \pi_{\mathrm{E}}^{\mathrm{FS}}$, $0 \le \pi_{\mathrm{I}}^{\mathrm{FS}} \le \pi_{\mathrm{I}}^{\mathrm{SS}}(C)$, $0 = \pi_{\mathrm{E}}^{\mathrm{SF}} \le \pi_{\mathrm{E}}^{\mathrm{SS}}(C)$, $0 = \pi_{\mathrm{E}}^{\mathrm{FF}} \le \pi_{\mathrm{E}}^{\mathrm{FS}}$, and $0 \le \pi_{\mathrm{I}}^{\mathrm{FF}} \le \pi_{\mathrm{I}}^{\mathrm{SF}}(C)$: A firm's profit is nonnegative (it can always choose not to produce); a competitor's success decreases a firm's profit; and a firm's success increases its profit.

Assumption (A7). *$\pi_{\mathrm{I}}^{\mathrm{SF}}(C)$ and $\pi_{\mathrm{I}}^{\mathrm{SS}}(C)$ are increasing in C:* When the incumbent succeeds, she benefits from her ability to produce at low cost: Her profit increases with her level of cost competence.

Assumption (A8). *There is a* ***cost competence hurdle,*** *denoted by C_H, such that if $C \le C_H$ then $\pi_{\mathrm{I}}^{\mathrm{SS}}(C) = \pi_{\mathrm{I}}^{\mathrm{FS}}$ and $\pi_{\mathrm{E}}^{\mathrm{SS}}(C) = \pi_{\mathrm{E}}^{\mathrm{FS}}$, and if $C > C_H$* then $\pi_{\mathrm{I}}^{\mathrm{SS}}(C) \ge \pi_{\mathrm{I}}^{\mathrm{FS}}$ and $\pi_{\mathrm{E}}^{\mathrm{SS}}(C) = 0$.

Assumption (A8) states that if the incumbent's cost competence is below the cost competence hurdle, and both firms succeed, then the profits of both firms are the same as if only the entrant had succeeded. Effectively, in this situation, we are assuming the incumbent finds it to her benefit not to implement the new technology. However, if her cost competence *exceeds* the cost competence hurdle, then we assume she finds it to her advantage to effectively drive the entrant out of the new product market when both firms are successful, driving the entrant's profit to zero.

While possibly unsettling to some readers, this assumption holds in the example of the supporting model presented in §4. Furthermore, there is empirical evidence that firms sometimes master a new technology but do not market it strongly. For example, Utterback states:

> Most threatened firms do participate in the new technology and often have preeminent positions in it . . . . they continue to make their heaviest commitments to the old . . . . (Utterback 1994, p. 194).

Utterback implies that the incumbent's lack of commitment to the new technology is suboptimal behavior, or at least is behavior that the firm should correct. As we will see later in §4, the model developed herein suggests a slightly different, but complementary, perspective: The incumbent's lack of commitment to the new technology may be optimal given the firms' existing competence levels. However, the incumbent makes the alternate decision to commit to the new technology if she holds sufficient cost competence. Before verifying that this assumption holds in the supporting model, we characterize the firms' investment decisions under the more generic model of technology competition.

3. The Firms' Optimal Investment Amounts

Let $\Pi_I(K_I, K_E)$ and $\Pi_E(K_I, K_E)$ denote the incumbent's and entrant's expected profits, respectively, as functions of the investment amounts. By enumerating the four outcomes of the technology competition, it follows that:

$$\Pi_I(K_I, K_E) = P_I P_E \pi_I^{SS}(C) + P_I(1 - P_E)\pi_I^{SF}(C) + (1 - P_I)P_E\pi_I^{FS} + (1 - P_I)(1 - P_E)\pi_I^{FF} - K_I, \quad (3)$$

$$\Pi_E(K_I, K_E) = P_I P_E \pi_E^{SS}(C) + P_I(1 - P_E)\pi_E^{SF} + (1 - P_I)P_E\pi_E^{FS} + (1 - P_I)(1 - P_E)\pi_E^{FF} - K_E. \quad (4)$$

Using Equations (1) and (2), and rearranging terms, (3) and (4) can be re-expressed as:

$$\begin{aligned}\Pi_I(K_I, K_E) &= \pi_I^{FF} - [1 - \exp(-r_E K_E)](\pi_I^{FF} - \pi_I^{FS}) \\ &+ [1 - \exp(-r_I K_I)]\,[\pi_I^{SF}(C) - \pi_I^{FF}] \\ &- [1 - \exp(-r_E K_E)]\,[1 - \exp(-r_I K_I)] \\ &\cdot [[\pi_I^{SF}(C) - \pi_I^{FF}] - (\pi_I^{SS}(C) - \pi_I^{FS})] - K_I, \end{aligned} \quad (5)$$

$$\begin{aligned}\Pi_E(K_I, K_E) &= [1 - \exp(-r_E K_E)]\pi_E^{FS} - [1 - \exp(-r_E K_E)] \\ &\cdot [1 - \exp(-r_I K_I)]\,[\pi_E^{FS} - \pi_E^{SS}(C)] - K_E. \end{aligned} \quad (6)$$

We seek the optimal response function for each firm, namely, the nonnegative investment amount that will maximize that firm's expected return as a function of the competitor's investment amount. In preparation for presenting the response functions, it will prove useful to define $R_I(C)$, R_E, $R_I^c(C)$, and $R_E^c(C)$ as follows (interpretations are given following Lemma 1): $R_I(C) \equiv r_I\,[\pi_I^{SF}(C) - \pi_I^{FF}]$, $R_E \equiv r_E\,\pi_E^{FS}$, $R_I^c(C) \equiv r_I\,[\pi_I^{SS}(C) - \pi_I^{FS}]$, and $R_E^c(C) \equiv r_E\,\pi_E^{SS}(C)$.

Lemma 1. *The optimal response functions for the incumbent and entrant, respectively, are:*

$$K_I(K_E) = \begin{cases} (\ln\,[R_I(C) + R_I^c(C)\,(\exp\,[r_E K_E] - 1)] - r_E K_E)/r_I \\ \quad \text{if } R_I(C) + R_I^c(C)\,(\exp\,[r_E K_E] - 1) > \exp(r_E K_E), \\ 0 \quad \text{otherwise.} \end{cases}$$

$$K_E(K_I) = \begin{cases} (\ln\,[R_E + R_E^c(C)\,(\exp\,[r_I K_I] - 1)] - r_I K_I)/r_E \\ \quad \textit{if } R_E + R_E^c(C)\,(\exp\,[r_I K_I] - 1) > \exp(r_I K_I), \\ 0 \quad \textit{otherwise.} \end{cases}$$

All proofs are given in Appendix 2.

Suppose the entrant decides not to invest: $K_E = 0$. Then, Lemma 1 says the incumbent will invest (a strictly positive amount) if and only if $R_I(C) > 1$. That is, $R_I(C)$ is a measure of the raw attractiveness of the incumbent's investment, with $R_I(C) = 1$ representing a hurdle level. R_E plays a similar role for the entrant.

Suppose the investment is on the borderline of being attractive in the raw for the incumbent ($R_I(C) = 1$). The Lemma 1 can be rewritten as saying the incumbent will invest if and only if $R_I^c(C) > 1$. Thus, we can interpret $R_I^c(C)$ as a measure of the competitive attractiveness of the investment (the superscript c denotes the presence of a competitor): The same interpretation applies to $R_E^c(C)$ for the entrant. That is, whether a firm invests depends on both the raw attractiveness and competitive attractiveness.

There are four possible investment zones: "Neither invests," "Only the incumbent invests," "Only the entrant invests," and "Both invest." (When we say "Only the incumbent invests," for example, this indicates the incumbent invests some strictly positive amount, while the entrant's investment is zero.) We first consider the case where $R_E \leq 1$.

THEOREM 1. *For $R_E \leq 1$, investment decisions, investment amounts, probabilities of success, and expected profits are as follows:*

Region	Incumbent	Entrant
	If $R_I(C) \leq 1$, then:	
Neither Invests	$K_I = 0$ $P_I = 0$ $\Pi_I = \pi_I^{FF}$	$K_E = 0$ $P_E = 0$ $\Pi_E = 0$
	If $R_I(C) > 1$, then:	
Only the Incumbent Invests	$K_I = [\ln R_I(C)]/r_I$ $P_I = 1 - 1/R_I(C)$ $\Pi_I = \pi_I^{SF}(C) - [1 + \ln R_I(C)]/r_I$	$K_E = 0$ $P_E = 0$ $\Pi_E = 0$

We next consider the case where $R_E > 1$. We show how the incumbent's innovative competence, R (recall that $R \equiv r_I/r_E$), in conjunction with the incumbent's cost competence C, can be used to define which firms invest. We also identify the firms' investment amounts, probabilities of success, and expected profits within each of the investment zones. But first, to aid in exposition and interpretation, define $R_A(C) \equiv R_E - R_I(C) + R_I^c(C)$. It will prove useful to give investment amounts, probabilities of success, and profits in terms of $R_A(C)$. Define $R_H(C) \equiv \pi_E^{FS}/[(\pi_I^{SF}(C) - \pi_I^{FF}]$ if $\pi_I^{SF}(C) > \pi_I^{FF}$, and as positive infinity if $\pi_I^{SF}(C) = \pi_I^{FF}$. Define $R_h(C) \equiv \pi_E^{FS}/[(\pi_I^{SF}(C) - \pi_I^{FF}) + (R_E - 1)(\pi_I^{SS}(C) - \pi_I^{FS})]$ if the denominator is strictly positive, and as positive infinity if the denominator equals zero. Interpretation of $R_H(C)$ and $R_h(C)$ follow Theorem 2. Note that $R_h(C) \leq R_H(C)$, since $R_E > 1$ and $\pi_I^{SS}(C) \geq \pi_I^{FS}$.

THEOREM 2. *For $R_E > 1$, investment decisions, investment amounts, probabilities of success, and expected profits are determined by R and C as shown in the table on the next page.*

To avoid uninteresting situations where the entrant would never invest, we will henceforth assume $R_E > 1$, and we will assume the entrant's competencies are fixed with c_E and r_E constant. Note from Theorem 2 that when $R_E > 1$, the investment zones are identified by whether the incumbent's cost competence, C, is above or below C_H, and by whether the incumbent's innovative competence, R, is above $R_H(C)$, between $R_h(C)$ and $R_H(C)$, or below $R_h(C)$. Thus, we can illustrate the results of Theorem 2 in a map such as shown earlier in Figure 1, where the two dimensions are C and R.

Recall that C_H was defined in (A8) as a cost competence hurdle. From Theorem 2, we see that $R_H(C)$ and $R_h(C)$ can similarly be interpreted as innovative competence hurdles. (Recall that $R_H(C) > R_h(C)$: Therefore, $R_H(C)$ is the bigger hurdle while $R_h(C)$ is the smaller hurdle.) However, C_H is a constant, independent of R, whereas both $R_H(C)$ and $R_h(C)$ are functions of C. In particular, these hurdles become nonlinear boundaries to the regions in Figure 1.

For example, assume $C \leq C_H$ (positioning us in the left half of Figure 1). By Theorem 2, if R falls short of the hurdle $R_H(C)$, then "Only the Entrant Invests," which is the *retrenchment* region: The incumbent has no chance of offering the new product. If R exceeds the hurdle $R_H(C)$, then "Both Invest," which is the *contingent retrenchment* region: She retrenches with the old technology, except under one contingency, when *only* she succeeds (in commercializing the new technology). In this region, by (A8), the incumbent finds it to her benefit *not* to implement the new technology if both firms are successful. Thus, for $C \leq C_H$, the hurdle $R_H(C)$ represents the nonlinear boundary between these two investment zones: As illustrated in Figure 1, $R_H(C)$ is a decreasing function of C, since $\pi_I^{SF}(C)$ is increasing in C and π_E^{FS} and π_I^{FF} are constants.

Next assume $C > C_H$ (positioning us in the right half of Figure 1). By Theorem 2, if R falls short of $R_h(C)$, then "Only the Entrant Invests," which is again the *retrenchment* region. If R falls between the hurdles $R_h(C)$ and $R_H(C)$, then "Both Invest," which is the *contingent domination* region: The incumbent dominates unless the entrant is the only firm to succeed. If both firms succeed, then, by (A8), the incumbent dominates in the sense that she drives the entrant's profits down to zero. However, by (A6), she does not necessarily realize monopoly profits.

If R exceeds the bigger hurdle $R_H(C)$, then "Only the Incumbent Invests," which is the *domination* region because the incumbent is guaranteed to continue as the technology leader. Thus, in Figure 1, for $C > C_H$, the hurdle $R_h(C)$ represents the boundary between "Only the Entrant Invests" and "Both Invest," and the hurdle $R_H(C)$ represents the boundary between "Both Invest" and "Only the Incumbent Invests." Figure 1 reflects the situation to be illustrated in §4, where $R_H(C)$ is a decreasing function of C, and $R_h(C)$ approaches $R_H(C)$ as C approaches C_H from above (at this point, $\pi_I^{SS}(C) = \pi_I^{FS}$).

Consider the implications and magnitudes of the hurdle levels $R_H(C)$ and C_H. The firm must exceed both to achieve domination. $R_H(C)$ is the ratio of the incremental profit that the entrant receives from being the sole successful firm (π_E^{FS}), to the incremental profit that the incumbent achieves from achieving success in isolation $[\pi_I^{SF}(C) - \pi_I^{FF}]$. In other words, if the entrant has more to gain in becoming a duopolist than the incumbent has to gain by enhancing her monopoly position, as is the case in the model presented by Arrow (1962), then this hurdle level exceeds one. When the hurdle level exceeds one, as will be the case in the example in the next section, the incumbent must, in effect, have higher innovative competence than the entrant in order to be willing to invest. With zero cost competence, she can't even reach the domination zone. Thus the model displays the "replacement effect" noted by

Table 1 Theorem 2 (continued)

Region	Incumbent	Entrant
	If $C \leq C_H$ and $R \leq R_H(C)$, or If $C > C_H$ and $R \leq R_h(C)$, then:	
Only the Entrant Invests (Retrenchment)	$K_I = 0$ $P_I = 0$ $\Pi_I = \pi_I^{FS} + (\pi_I^{FF} - \pi_I^{FS})/R_E$	$K_E = (\ln R_E)/r_E$ $P_E = 1 - 1/R_E$ $\Pi_E = \pi_E^{FS} - (1 + \ln R_E)/r_E$
	If $C \leq C_H$ and $R > R_H(C)$, then:	
Both Invest (Contingent Retrenchment)	$K_I = (\ln [R_I(C)/R_E])/r_I$ $P_I = 1 - R_E/R_I(C)$ $\Pi_I = \pi_I^{FS} + [\pi_I^{SF}(C) - \pi_I^{FS}]/R_E - (1 + \ln [R_I(C)/R_E])/r_I$	$K_E = (\ln R_E)/r_E$ $P_E = 1 - 1/R_E$ $\Pi_E = \pi_E^{FS} - (1 + \ln R_E)/r_E$
	If $C > C_H$ and $R_h(C) < R < R_H(C)$, then:	
Both Invest (Contingent Domination)	$K_I = (\ln [R_E R_I^c(C)/R_A(C)])/r_I$ $P_I = 1 - R_A(C)/[R_E R_I^c(C)]$ $\Pi_I = [-R_A(C) + R_E \pi_I^{SS}(C)\ r_I$ $+ r_I^2 (\pi_I^{FF}\ \pi_I^{SS}(C) - \pi_I^{SF}(C)\ \pi_I^{FS}$ $- R_a(C) \ln R_E + R_A(C) \ln [R_A(C)/R_I^c(C)])]/[R_A(C) r_I]$	$K_E = (\ln [R_A(C)/R_I^c(C)])/r_E$ $P_E = 1 - R_I^c(C)/R_A(C)$ $\Pi_E = (R_E - R_I(C)$ $- R_I^c(C) \ln [R_A(C)/R_I^c(C)])/[R_I^c(C) r_E]$
	If $C > C_H$ and $R \geq R_H(C)$, then:	
Only the Incumbent Invests (Domination)	$K_I = [\ln R_I(C)]/r_I$ $P_I = 1 - 1/R_I(C)$ $\Pi_I = \pi_I^{SF}(C) - [1 + \ln R_I(C)]/r_I$	$K_E = 0$ $P_E = 0$ $\Pi_E = 0$

Arrow (1962): Since the incumbent's new product cannibalizes her old product, she may have less inherent incentive to innovate, as compared to an entrant firm.

A new insight offered by our work, however, is the implication regarding the importance of cost competence. The incumbent cannot reach *either* the domination or contingent domination zones without achieving cost competence at or above the hurdle level, regardless of the incumbent's innovative competence level. While the innovative competence hurdle $R_H(C)$ decreases in C, the cost competence, the reverse does not hold: The cost competence hurdle C_H is unaffected by R, the innovative competence. The firm can trade off a lower level of innovative competence by holding a higher level of cost competence, and still achieve domination. However, there is no substitute for a lack of cost competence at this level: If the incumbent's cost competence falls below the hurdle level, the firm is relegated to contingent retrenchment, at best.

The value of reaching the domination zone is further highlighted as follows:

Theorem 3. *The expected profit level of the incumbent, viewed as a function of her cost competence C and starting from any point in the "contingent retrenchment" zone, makes a discontinuous jump upward as C passes through the hurdle C_H.*

As the incumbent projects her expected profit level as a function of her cost competence C, she observes a discontinuous jump in expected profit when transitioning from the "Both Invest" zone labeled "contingent retrenchment" to the "Only the Incumbent Invests" zone labeled "domination." At this boundary, the incumbent's cost competence level thwarts the investment of the entrant firm. We now develop an illustration to highlight the insights offered by the preceding theorems.

4. An Example of a Supporting Model: Vertically Differentiated Products

To establish the details of a firm's competence map, a supporting product market model is needed to determine how competing firms will set prices and production quantities on non-identical, competing products (the old and new). The supporting model determines the role of cost competence, since the supporting model establishes further details such as: 1) the extent to which consumers perceive the new product differently from the old product, 2) whether the new product is a substitute or complement to the old product, and 3) whether the two firms compete on price or quantity. We use a standard model from marketing and economics for this purpose.

Our supporting model is based on vertically differentiated products, a concept developed by Gabszewicz and Thisse (1979) and Shaked and Sutton (1982). We assume that product quality is described by a single parameter, denoted herein as v. A customer will buy at most one of the products offered for sale. Each customer has a reservation price (utility), denoted by u, for each possible product. Each customer buys the product offering him the highest positive surplus, and buys nothing if both surpluses are negative. (Surplus is the difference between a customer's reservation price for the product, and the price at which the product is offered.) We assume that the reservation price of a customer of type θ for a product of quality level v is given by $u(\theta, v) = v\,(100 - \theta)$ for $0 \le \theta \le 100$: Customer type 0 has the highest reservation price (of 100 v) and the reservation prices decrease linearly to zero (for customer type 100). We also assume that the customer types are uniformly distributed in the market so that, in the case of only a single product being offered, its reservation price curve is its inverse demand curve.

Moorthy (1988) shows that when multiple products of varying quality levels are sold, customers are partitioned into distinct market segments. The product of highest quality is sold to customers with the highest reservation prices (lowest θs). Each subsequent market segment is associated with lesser product quality, and decreasing customer willingness to pay (increasing θ).

In our model there are two products, the incumbent's old product, and the new product (which may be marketed by the incumbent and/or the entrant, depending on who is successful). Henceforth, we work solely with a numerical example, to keep the exposition clear. We shall verify that our assumptions hold in this example here.

Assume the maximum reservation price for the old product is 70 and the highest reservation price for the new product is 100. That is, the incumbent's old product is of quality $v_I^o = 0.7$ (the superscript "o" will be used to denote parameters associated with the old product), while the new product is of quality $v_I = v_E = 1.0$. We assume throughout this paper that production cost is proportional to the quantity produced: Unit cost equals marginal cost equals average cost. Assume the unit cost of the old product is $c_I^o = 40$, and the entrant's cost for the new product is $c_E = 57$. The incumbent's cost for the new product will be established by her level of cost competence.

The Four Possible Outcomes When the Firms Produce at Equal Cost

Assume for the moment that if both firms are successful they produce the new product at equal cost, so $C = 0$ and $c_I = c_E = 57$. If both firms fail, the incumbent offers only the old product as a monopolist. The old product's reservation price curve is a linear inverse demand curve, so the standard result is obtained: The incumbent prices at the average of her cost and the price intercept of the inverse demand curve. Thus she sells 21.4 units of the old product at price $p_I^o = 55$, to customers of type $0 \leq \theta \leq 21.4$, resulting in a monopoly profit of $\pi_I^{FF} = 321$.

Next consider the case when only the entrant succeeds. The entrant offers only the new product, while the incumbent offers only the old product. Firms are assumed to simultaneously set prices to maximize profits. In other words, each firm determines its best pricing response, given the price set by the competitor for the other product.

Moorthy (1988) shows that under these assumptions, each firm can be thought of as acting like a monopolist who faces a fixed price substitute product, in the sense that a firm prices at the average of its marginal cost and the price at which the entire market goes to the other product. His Equations (4.3) and (4.4) (p. 153), when adapted to our problem, suggest that the incumbent sells her (lower quality) product at price $p_I^o = 42.7$ and the entrant sells his (higher quality) product at price $p_E = 64.8$. In particular, a customer of "type 26.2" is (roughly) indifferent between the two products: $u(26.2, v_I^o) - p_I^o \approx 9 \approx u(26.2, v_E) - p_E$. Customers in the interval (0, 26.2) are willing to pay more for quality as compared to the customer of "type 26.2," and thus customers in the interval (0, 26.2) buy the entrant's higher quality product rather than the incumbent's lower quality product. A customer of "type 39" is indifferent between buying the incumbent's old product and nothing: $u(39, v_I^o) - p_I^o = 0$. Customers in the interval (26.2, 39) are willing to pay more for quality as compared to the customer of "type 39," and thus customers in the interval (26.2, 39) buy the incumbent's lower quality product rather than nothing. Customers in the interval (39, 100) buy nothing.

The incumbent's profit is $\pi_I^{FS} = 35$ and the entrant's profit is $\pi_E^{FS} = 202$. The entrant's new product has had a severe detrimental effect on the incumbent: Her profit drops by nearly 90%. Total industry profits drop by 25% while the number of units sold nearly doubles.

A third possibility is that only the incumbent succeeds. She has the choice of selling only the old product, both the old product and the new product, or only the new product. In this situation the incumbent finds she derives her maximum profit of 462 by dropping the old product, and selling only the new product as a monopolist. (See Schmidt (1998) for details.) The profit of $\pi_I^{SF}(C) = 462$ is an increase of 43% over the incumbent's profit when only her old product was sold.

Next consider what happens under the fourth possible outcome, where both firms are successful with the new technology. In this case the incumbent has the choice of selling both the old and new products, or only one product. We assume the incumbent first decides which product(s) to sell, and then sets the prices for the products. For each possible combination of products to offer, the incumbent considers what the resulting profits will be, and picks the best of these. In each scenario, the incumbent determines the equilibrium prices and the resulting profits.

If the two firms produce at equal cost, and if they simultaneously set price, as assumed herein, then the incumbent cannot sell a strictly positive quantity of the new product unless she drives its price down to cost. (This is the standard economic result known as the Bertrand equilibrium.) Driving the new product price down to cost will only reduce the incumbent's profit on sales of the old product. (Lowering the price of the new product makes the new product more attractive to customers, such that some customers drop the old in favor of the new.) Thus if the incumbent sells the new product, she makes no profit from it, and hurts her profitability on the old product. Therefore, it is in the incumbent's best interests *not* to offer the new product when both firms are successful. In other words, the market outcomes and profits are the same as when only the entrant succeeds: $\pi_I^{SS}(C) = \pi_I^{FS} = 35$ and $\pi_E^{SS}(C) = \pi_E^{FS} = 202$.

Thus, we see that one part of assumption (A8) holds in this example: When the incumbent can only produce the new product at the same cost as the entrant, it is optimal for her to back away from the new technology if both firms succeed. However, we also want to examine her behavior when she has a cost advantage in producing the new product.

The Four Possible Outcomes When the Incumbent Has a Cost Advantage

Next consider the outcomes when the incumbent has a cost advantage in producing the new product, i.e., $C > 0$, such that $c_I < 57$. (The alternate assumption, that the incumbent is at a relative cost *disadvantage,* need not be excluded from a modeling standpoint, but would only further emphasize the importance of cost competence as compared to the results given herein.)

More specifically, for purpose of illustration, assume the incumbent holds a 5% cost advantage ($c_I = 54.15$). When neither firm succeeds, or when only the entrant succeeds, the incumbent's cost competence has no effect on the firms' profits, since she doesn't implement the new technology. When only the incumbent succeeds, she is able to use this lower unit cost to her advantage, and she makes a monopoly profit of $\pi_I^{SF}(C) = 526$ from selling only the new product. For $C > 0$, her profit is $\pi_I^{SF}(C) = (4{,}300 + 57\, C)^2 / 40{,}000$, confirming the last part of Assumption (A6) and the first part of (A7).

Now consider what happens if both firms succeed. When she holds strictly positive cost competence, the incumbent considers the option of selling the new product at the entrant's cost, thereby realizing a positive profit from those sales. By selling the new product at the entrant's cost, the incumbent shuts the entrant out of the market entirely, giving him zero sales and zero profit. (Technically, the incumbent sells at some infinitesimally small amount below the entrant's cost, unless the incumbent's monopoly price for the new product is actually below the entrant's cost, in which case she sells the new product at the monopoly price.)

In our example, selling the new product at the entrant's cost of 57 gives the incumbent a margin of 5% (2.85 units) on sales of the new product, to customers in the interval (0, 43). At the same time, it drives the sales of her old product to zero. (To see this, note that a customer of type $\theta = 43$ holds zero surplus for the new product when sold at a price of 57, and holds zero surplus for the old product when sold at the incumbent's cost of 40. Since the slope of the reservation price curve is steeper for the new product, customers of type $\theta < 43$ will have greater surplus for the new product than for the old product, and will thus buy the new product. Customers of type $\theta > 43$ will have negative surplus for the old product as well as the new product, and will thus buy nothing.)

The incumbent's resulting profit is $\pi_I^{SS}(C) = 2.85\,(43) = 123$. Since this is greater than the profit (of 35 units) the incumbent would receive by selling only the old product and letting the entrant take the new product market, she decides to sell the new product at the entrant's cost. This drives the entrant out of the market entirely.

The Cost Competence Hurdle

There will be some cutoff point, or level of cost competence, where the incumbent becomes indifferent between the following two options: 1) giving the entrant the new product market to himself when both firms succeed, versus 2) driving the entrant out of the new product market entirely. This cutoff point will be denoted as the incumbent's *cost competence hurdle,* C_H. For $C \le C_H$ the entrant's success yields him the same profit regardless of whether the incumbent succeeds or not. For $C > C_H$ the entrant's success yields him zero profit when both firms succeed. In this illustration, the cost competence hurdle is $C_H = 1.43\%$. (The incumbent simply needs to recoup the 35 units of profit she loses on sales of the old product. Selling the new product at the entrant's cost of 57 yields 43 units sold, such that a margin of 1.43% of 57, is sufficient.) For $C_H < C < 75.44$, the incumbent sells at the entrant's cost, receiving profit $\pi_I^{SS}(C) = 24.51\, C < \pi_I^{SF}(C)$, while for $C > 75.44$ the incumbent's monopoly price is below the entrant's cost, such that $\pi_I^{SS}(C) = \pi_I^{SF}(C)$. This confirms the first part of (A6), and, recalling that $\pi_I^{SS}(C) = \pi_I^{FS} = 35$ for $0 < C \leq C_H$, this also confirms the second part of Assumption (A7).

To show the remaining parts of Assumption (A6), note that $\pi_I^{FS} = 35 < 321 = \pi_I^{FF}$, $\pi_E^{SS}(C) = 0 < 202 = \pi_E^{FS}$ for $C \leq C_H$ and $\pi_E^{SS}(C) = 202 = \pi_E^{FS}$ for $C > C_H$, $\pi_I^{FS} = 35 = \pi_I^{SS}(C)$ for $C \leq C_H$ and $\pi_I^{FS} = 35 < \pi_I^{SS}(C)$ for $C > C_H$. Also, the above discussion shows Assumption (A8) holds for this example.

The Detailed 2-D and 3-D Competence Maps

In the fashion just described, we calculate the profits accruing to each firm for various cost competence levels. These profit numbers are fed into the equations for investment amount, probability of success, and expected profit as given in Theorem 2. The entrant's investment effectiveness parameter is assumed to be fixed at $r_E = 0.03$, while the incumbent's investment effectiveness parameter is varied from $r_I = 0.03$ to $r_I = 0.05$, giving her an innovative competence ranging from $R = 1.00$ to $R = 1.67$. Calculating the positions of the boundaries C_H, $R_H(C)$, and $R_h(C)$, we obtain the competence map shown previously in Figure 1. (The tick marks on the horizontal axis of Figure 1 represent $C = 0\%$ (at the origin), $C = 1\%$, $C = 2\%$, and $C = 3\%$, respectively. The tick marks on the vertical axis represent $R = 1$ (at the origin), $R = 1.2$, $R = 1.4$, and $R = 1.6$, respectively.)

We now illustrate Theorem 3 by plotting the expected profit to each player as a function of the incumbent's cost competence C. We hold the innovative competence R constant at $R = 1.67$, which corresponds to moving horizontally along the top of Figure 1. By Theorem 2, the entrant receives the same expected profit throughout the region $C \leq C_H$ (inside the contingent retrenchment zone), while the incumbent's return increases slightly because $\pi_I^{SF}(C)$ increases in C. As C passes through the hurdle into the domination zone, the entrant's investment level drops to zero while the incumbent's investment level changes to a new higher level. The results are plotted in Figure 2. Note that the incumbent's expected profits continue to increase (as can be verified by Theorem 2, using the definition for $R_I(C)$ and noting that $\pi_I^{SF}(C)$ is increasing in C).

Figure 2 Expected Profits as a Function of Cost Competence for R = 1.67

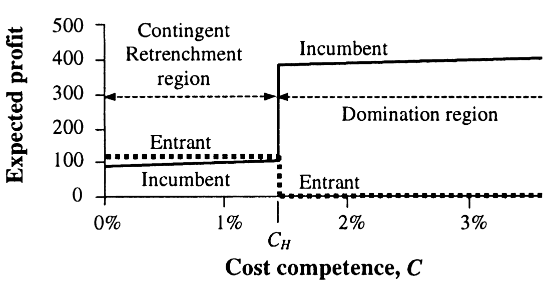
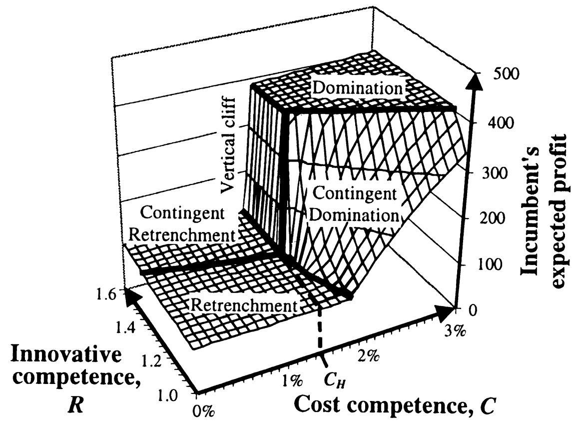


Figure 3 Incumbent's Expected Profit as a Function of R and C.



The 3-dimensional map of the incumbent's expected profit, as a function of her competencies, is plotted in Figure 3. (Looking down at the top on this 3-dimensional map yields the 2-dimensional picture as previously given in Figure 1.) Note how the expected profit in the contingent retrenchment zone is only incrementally higher than that in the retrenchment zone, while expected profit in the contingent domination region has a steep slope. The jump in profit at the boundary between the contingent retrenchment and domination zones is reflected by the vertical cliff separating these regions. One important consequence of this example is that the expected profits are not concave functions of the competencies. In particular, it would be folly to approach the problem of setting optimal competency levels by merely seeking solutions to the first order conditions.

5. Relationship to the Literature

The operations literature offers many detailed models of an organization's operating environment and often suggests ways to operate more efficiently. This paper provides an avenue for understanding the strategic significance of that literature. In particular, we develop a model of technology competition in which a firm's cost competence and innovative competence are critical strategic parameters. And many papers in the operations literature can be viewed as suggesting ways that a firm can improve those competencies.

Fine and Freund (1990) suggest that some firms invest in flexible manufacturing equipment not so they can produce a wide variety of products at a *given* point in time, but rather so they can produce a wide variety of products *over* time. This flexibility provides cost competence, the ability to produce the new generation of product at lower cost, by avoiding additional equipment costs generally associated with a new product line.

Ha and Porteus (1995), Krishnan et al. (1997), and Loch and Terwiesch (1998) seek efficient ways to manage the information passed between different organizations working, perhaps concurrently, on a new product development project. These are ways a firm can improve its innovative competence and possibly also its cost competence.

Ulrich et al. (1993) show that a firm proficient in structured methodologies such as "design for manufacturability" can introduce products that are functionally equivalent to, but less costly than, competitive offerings. Ulrich and Pearson (1998) show empirically that different design practices and capabilities lead to different manufacturing costs for new products. In short, design can strongly affect cost competence.

Pisano and Wheelwright (1995) assert that a firm that emphasizes the role of process development in the introduction of new products positions itself further down on the learning curve. This translates into lower-cost new products, and, therefore, higher-cost competence.

Womack, et al. (1990) argue that developing skills in supplier management, or in lean manufacturing, might also generate a sustainable cost advantage. Rather than being product specific, this knowledge is likely transferable to a new product generation, implying cost competence.

The papers cited comprise only a small sampling of the papers that say something about how a firm can increase its competencies. Cohen and Levinthal (1994) identify a different notion of competence called absorptive capacity. In their model, higher absorptive capacity gives the firm a better assessment of the likelihood that an uncertain, but desirable, new technology will become available, and a higher profit from the new technology if it materializes. Their model seeks the optimal level of absorptive capacity, while ours takes competencies as being fixed. Their model of technology competition does not allow the firms to vary their amounts invested in commercializing a newly available technology, and cost competence does not play a direct role in their analysis.

We ignore certain issues in new product development that are covered by other papers. For example, we do not consider time to market, and we assume that product performance will be the same for both firms if they are successful. Cohen et al. (1996) derive some interesting insights into the trade-offs between development team sizes, time to market, and product performance. Cohen et al. (1997) develop a system for managing the new product development process for consumer packaged goods. While those papers address an essentially single firm setting, Cohen and Whang (1997) examine the product design question when there will be competition in its after-sales service.

We assume a new technology is available and the micro question is how much each firm will invest in commercializing it. Thus, our model ignores the possible role of search, information processing, and the random arrival of new technologies. Such phenomena are addressed in Lippman and McCardle (1987, 1991) and McCardle (1985) in a single firm setting, and in Mamer and McCardle (1987) in a competitive setting.

An important feature of our model is the potential cannibalization of the incumbent's old product by the new one, also called the replacement effect. As discussed previously, this effect suggests that an entrant has more incentive to invest in new technology than does an incumbent. However, in the case of patent races, in which the first firm to succeed obtains the bulk of the returns from success, there can be an offsetting "efficiency effect" (e.g., see Tirole 1988, Chapter 10): If the entrant wins the patent race, the incumbent can lose more, (by being reduced from a monopolist to a duopolist), than the entrant gains by becoming a duopolist. Thus, the efficiency effect may offset the replacement effect—see Gilbert and Newbery (1982) and Reinganum (1984) for how the details of the model determine the relative strength of the effects. Reinganum (1985) extends the analysis of such races to a dynamic model over a sequence of innovations, showing that, with every new innovation, the incumbent invests less than the challengers. Put another way, in a patent race, cost competence plays a relatively minor role: It increases the incentive for the incumbent to invest, but without the possibility of both firms offering the new product simultaneously, it is not clear that an incumbent's very high cost competence will be enough to deter investment by an entrant. (If the entrant succeeds first, the incumbent's cost competence is of no consequence.)

Our model is closely related to the one analyzed by Ghemawat (1991). He assumes each firm can decide whether or not to pursue commercialization of the new technology, but not how much to invest. While we assume the event that one firm succeeds is independent of whether the other succeeds, he allows dependencies, which can capture spillovers, among other things. He shows that if these events are independent, then the entrant is more likely to introduce the new product. However, he does not develop an explicit equilibrium to his model and he does not directly address the impact of changes in the firms' competencies.

Scherer (1992) summarizes empirical evidence suggesting that entrants innovate at a disproportionate rate (more innovations per million dollars of R&D), but that established firms may be more successful in subsequent process improvement. Established firms venturing into new markets (entry by diversification) seem to have a higher success rate than de novo entrants (Geroski 1995). In short, it is generally accepted that entrants, or threats of potential entrants, help drive the "winds of creative destruction," as Schumpeter (1942) called the process by which innovative progress displaces mainstream technologies (Reinganum 1983).

Utterback (1994) suggests incumbents may simply fail to recognize the merits of, or fail to adapt to, a superior new technology. Because the incumbent is so focused on (or entrenched with) the existing product, she may be less likely to be successful in implementing the new technology, even though she may have been at the forefront in discovering it.

Henderson and Clark (1990) found incumbents may be particularly ineffective in dealing with "architectural change," created when interactions and linkages between components are altered and new interfaces are constructed, even though the functions of individual components are unchanged. Analogously, Bower and Christensen (1995) found dominant firms unable to cope with "disruptive technologies," for which the rate of performance improvement exceeds the rate at which customer performance requirements are advancing. For example, in the disk drive industry, the incumbent was so focused on the needs of *today's* customers (e.g., desktop computer users) that it failed to recognize how new, smaller drives could meet the needs of *tomorrow's* customers (laptop computer users, in addition to desktop users).

Tushman and Anderson (1986) suggest the incumbent is more likely to initiate "competence-enhancing" technological discontinuities, which are order-of-magnitude improvements that build on knowledge required to produce the existing product. "Competence-destroying" discontinuities are dependent upon the mastery of new skills and capabilities, and are more likely initiated by entrants. In the context of our model, architectural change, disruptive technologies, and competence-destroying discontinuities represent technologies for which the incumbent is apparently positioned in a vulnerable location on the competence map.

Thus, the question of why an incumbent may fail to sustain its technology leadership has been addressed in the literature from a number of perspectives. A stream of economics literature explores how this failure can be the result of optimal behavior on the part of incumbents. Firms are profit maximizers, acting optimally within their environment, given the incentives they face. The issue is to determine how certain aspects of the environment, or changes within that environment, affect the firm's incentives to innovate.

The management of technology field focuses more on the internal aspects of a firm's behavior, to identify and pinpoint specific factors that caused firms to fail (or to succeed). This literature is not so ready to assume that firms act optimally, but sets out to show firms what they would do if they really *were* to act optimally.

By synthesizing the studies of individual firms and industries, more general lessons are learned that can be applied more broadly.

Of course, one could argue that these really aren't divergent perspectives. The economics literature assumes firms act optimally *given* what they know, while the management of technology literature is intent on *expanding* what they know. The first research paradigm seeks to explain market behavior and gain insight through rigorous analytical modeling, but to achieve this rigor often needs to make numerous assumptions regarding the firm's behavior. The second is less willing to make these assumptions and rather delves inside the firm (and its industry) in pursuit of a more literal framework for explaining market outcomes, but may sacrifice the exactitude of the intricate mathematical model.

We attempt to bring an operations perspective to bear on the question of why an incumbent firm might fail to sustain its technology leadership position. The operations field relies heavily on analytical modeling in deriving optimal solutions, and thus it is natural to incorporate into this work the economics perspective that the firm's actions can be modeled as resulting from optimal behavior. At the same time, in the spirit of the management of technology literature, this paper highlights for firms an aspect of their internal behavior that they may want to rethink. Heretofore, some firms appear to have held the notion that the pursuit of cost leadership is separate and distinct from the pursuit of technology leadership. This work shows how a focus on cost (more specifically, on cost competence) can be critical even in an environment where innovation is anticipated.

6. Discussion

Several industry examples seemingly support the inferences put forth herein, while at the same time point to numerous model limitations and possible refinements. In a grossly simplified way, this model provides some insight as to how Intel's internal competencies may have contributed to its technology leadership and high profitability. Intel has stood virtually alone in the manufacture of high-end microprocessors for desktop computers, relegating competitors to selling "yesterday's" high-end product. If any high-tech firm can rightly claim to have positioned itself in the domination zone over the past decade, it would appear to be Intel.

Consider how Intel is positioned along the dimension of innovative competence, which measures the firm's ability to achieve a "high" probability of success with a "low" investment. At first glance, it might seem Intel is not very well positioned along this dimension, as its investment in a new generation of microprocessor appears to be anything but low. In addition to over $1 billion per year in engineering expenses, a new fabrication facility now costs more than $1 billion and construction must be initiated before technology development is complete.

But recall that the firm's position on the competence map is determined relative to its competition. Would-be competitors also face such costs (the term would-be is used because Intel has faced no real competitive products at the high-end, other than sporadic attempts such as the PowerPC™ and AMD's K-6™). Additionally, consider the probability of success. Would-be competitors can count on Intel's next generation every three to four years: The Intel286™ in 1982, the Intel386™ in 1985, the Intel486™ in 1989, the Pentium™ in 1993, and the Pentium II in 1997. In considering the possibility of leapfrogging Intel, would-be competitors thus face a firm whose probability of success in the next generation appears virtually assured.

Next consider Intel's cost competence. At first glance one might argue that AMD and Cyrix are lower-cost firms, since their microprocessors sell at lower prices. However, just because a product sells for less doesn't mean it is cheaper to make. There are a number of reasons why Intel might be able to sell at a higher price and enjoy dramatically larger margins than its competitors. Furthermore, the debate about which firm is the low cost producer relative to *today's* (lower-end) product really isn't pertinent. The pertinent cost is the cost of *tomorrow's* product, the new *high-end* product. Since the would-be competitors are not producing *today's* high-end product, it would appear relatively more difficult for them to establish a cost advantage with tomorrow's high-end product.

Intel has a history of driving down the production cost of a given product generation over time. This is achieved through efforts such as their "copy-exact" program, whereby a process improvement developed in one facility (or engineering laboratory) is copied exactly to achieve the same gain at other facilities. This aggressiveness contributes to the cost competence Intel (presumably) holds. The firm is sending a strong signal to would-be competitors regarding cost levels that would be needed to compete over the life of the next generation of product.

Examples are not limited to high-tech. The steel making industry was slow to adopting new technologies, until entrants such as Chaparral Steel came along with lower-cost mini-mills. Now an incumbent, Chaparral realizes it must further push down cost to sustain its leadership. Chaparral's emphasis on low cost contributes not only to considerable process innovation, but notably, also contributes to product innovation. As their founder and CEO Gordon Forward states,

> ". . . . if we are to survive in a world market, then we must be low-cost producers of comparable products, and thus the productivity 'focus' is vital. In the case of my own company, Chaparral Steel, high productivity has led to greater flexibility, *more products*, shorter production runs, and better quality" (Forward 1985, p. 112, emphasis added).

Their development of Microtuff 10 steel (Bowen et al. 1994) offers an example of how product innovation and process innovation often progress hand-in-hand.

Thus, qualitatively, the model does appear to reflect some industry situations. However, there any many aspects of the competitive environments faced by Intel and Chaparral that our model does not consider. For example, Intel and Chaparral face a *series* of new investment opportunities, rather than a single decision as we assume. A firm may alternate between being a technology leader, part of a pure competition, and an entrant. Furthermore, it seems plausible the firm might invest even though there is no prospect for returns in the current period, just to position itself more favorably for investment in future technologies. In other words, the investment itself may lead to enhanced competence. A dynamic model might better address these issues.

We have assumed there is only one new technology that the firm can choose to make an investment in. In reality, there may be a variety of technological options available to a firm, ranging from minor process improvement to drastic technological change. Furthermore, the firm may play a role in developing those options, rather than choosing from among an exogenously generated stream. The firm may also face a variety of (potential) competitors, some highly competent relative to minor innovation, and others highly competent with more drastic innovation. The incumbent may have to evaluate how its competencies position itself with regard to each type of innovation, and relative to each competitor.

In the model developed herein, the outcomes have been intentionally characterized as polar extremes or discrete events. In real life, there may be a continuum of possibilities. For example, our model assumes the market is either monopolistic, or firms simultaneously set price. In reality, there may be multiple competitors, with room for each firm to make a profit through differentiation, even if multiple firms are successful. We assume that a firm either achieves full success or experiences complete failure in mastering the new technology. Success may not be quite that simple: The degree of success may be measured by the firm's time-to-market, the product's performance, or by the resulting unit production cost.

The illustration given in §4 represents only one example of the way in which competition might play itself out. A realistic possibility not accounted for is that a high-tech firm may increase its competencies by offering a new technology that it has just mastered. Thus, an incumbent may pursue a new product specifically to develop its technical skills. The firm thereby keeps open the possibility of regaining its leadership position two or more generations into the future. In this case, the income stream resulting from success (or failure) in mastering the new technology will not be precisely as modeled herein. However, what this model does capture is the notion that a successful entrant reduces the profit that accrues to the successful incumbent, and the reality that an incumbent's cost competence has a negative impact on the successful entrant. While there may be other models to derive the exact profit numbers, qualitatively these effects seem to represent a plausible outcome.

As the above discussion suggests, there are many factors outside this model that may have contributed to the successes of Intel and Chaparral Steel. (For example, it has been suggested that Intel faces increasing, rather than decreasing, returns to scale—see Arthur

1996). However, by turning up the intensity on specific aspects of the firm's competitive environment, we have attempted to identify insights that might otherwise be blurred by extraneous, complicating factors. In this regard, our results suggest technology leadership may not be as separate and distinct from cost leadership as some firms presume.[1]

Appendix 1: Summary of Notation

c_E and c_I = unit cost (c) of the entrant's (E) and incumbent's (I) new product, respectively.

c_I^o = unit cost (c) of the incumbent's (I) old (o) product.

C = the incumbent's % cost competence (her % cost advantage for the new product).

K_E and K_I = investment cost (K) expended by the entrant (E) and incumbent (I), respectively.

π_E and π_I = expected profit (π) for the entrant (E) and incumbent (I), respectively.

π_E^{FF}, π_E^{SF}, π_E^{FS}, $\pi_E^{SS}(C)$, π_I^{FF}, $\pi_I^{SF}(C)$, π_I^{FS}, and $\pi_I^{SS}(C)$ = profit (π), prior to subtracting investment, for the entrant (E) or incumbent (I), when the incumbent succeeds (S) or fails (F), as indicated by the 1st superscript, and the entrant succeeds (S) or fails (F), as indicated by the 2nd superscript.

P_E and P_I = probability (P) that the entrant (E) and incumbent (I) will succeed, respectively.

p_E and p_I = price (p) of entrant's (E) and incumbent's (I) new product, respectively.

p_I^o = price (p) of incumbent's (I) old (o) product.

R = the incumbent's innovative competence, or investment effectiveness ratio, $R = r_I/r_E$.

$R_A(C) = R_E - R_I(C) + R_I^c(C)$.

$R_H(C)$ = an innovative competence hurdle, $R_H(C) \equiv \pi_E^{FS}/[\pi_I^{SF}(C) - \pi_I^{FF}]$ if $\pi_I^{SF}(C) > \pi_I^{FF}$, and $R_H(C) \equiv$ positive infinity if $\pi_I^{SF}(C) = \pi_I^{FF}$.

$R_h(C)$ = an innovative competence hurdle, $R_h(C) \equiv \pi_E^{FS}/[(\pi_I^{SF}(C) - \pi_I^{FF}) + (R_E - 1)(\pi_I^{SS}(C) - \pi_I^{FS})]$ if the denominator is strictly positive, and $R_h(C) \equiv$ positive infinity if it is zero.

r_E and r_I = investment effectiveness of the entrant (E) and incumbent (I), respectively.

R_E and $R_I(C)$ = parameters that must exceed one for the entrant (E) or incumbent (I), respectively, to invest when the competitor doesn't invest: $R_E = r_E\, \pi_E^{FS}$ and $R_I(C) = r_I\, [\pi_I^{SF}(C) - \pi_I^{FF}]$.

$R_E^c(C)$ and $R_I^c(C)$ = parameters indicating whether the entrant (E) or incumbent (I), respectively, should invest when the competitor (c) invests: $R_E^c(C) = r_E\, \pi_E^{SS}(C)$ and $R_I^c(C) = r_I\, (\pi_I^{SS}(C) - \pi_I^{FS})$.

θ = a parameter that represents a customer's willingness to pay for product quality.

u = the customer's utility or reservation price for a product.

v = a parameter representing the quality of a product.

v_E and v_I = quality level of the entrant's (E and incumbent's (I) new product, respectively.

v_I^o = quality level of the incumbent's (I) old (o) product.

Appendix 2: Proofs

Proof of Lemma 1. Given the entrant's investment $K_E \geq 0$, the incumbent seeks to maximize her expected return Π_I by setting her investment K_I, subject to the investment K_I being nonnegative. By Equation (5), her optimization problem is:

$$\max_{K_I} \Pi_I(K_I, K_E) = \pi_I^{FF} - [1 - \exp(-r_E K_E)]\,(\pi_I^{FF} - \pi_I^{FF})$$
$$+ [1 - \exp(-r_I K_I)]\,[\pi_I^{SF}(C) - \pi_I^{FF}] - [1 - \exp(-r_E K_E)]$$
$$[1 - \exp(-r_I K_I)]\,[(\pi_I^{SF})(C) - \pi_I^{FF}) - (\pi_I^{SS}(C) - \pi_I^{FS})] - K_I$$

subject to: $K_I \geq 0$.

Taking the 2nd derivative of the objective function with respect to the decision variable yields:

$$\partial^2 \Pi_I/\partial K_I^2 = -r_I^2\,[\pi_I^{SF}(C) - \pi_I^{FF}]\exp(-r_E K_E)\exp(-r_I K_I) - r_I^2$$
$$[\pi_I^{SS}(C) - \pi_I^{FS}]\,[1 - \exp(-r_E K_E)]\exp(-r_I K_I).$$

The above result is nonpositive when $K_I \geq 0$. Thus any nonnegative solution to the first order condition is optimal. Similarly, if a solution to the first order condition is nonpositive, then it is optimal to invest nothing: $K_I(K_E) = 0$. The first order condition results in

$$\exp(r_I K_I) = [r_I\,(\pi_I^{SF}(C) - \pi_I^{FF} + r_I\,[\pi_I^{SS}(C) - \pi_I^{FS}]$$
$$(\exp[r_E K_E] - 1)]/[\exp(r_E K_E)],$$

for which there is a strictly positive solution iff

$$r_I[\pi_I^{SF}(C) - \pi_I^{FF}] + r_I\,[\pi_I^{SS}(C) - \pi_I^{FS}]\,(\exp[r_E K_E] - 1) > \exp(r_E K_E).$$

When the inequality holds, the solution to the first order condition is unique and is given as follows:

$$K_I(K_E) = (\ln\,[r_I(\pi_I^{SF}(C) - \pi_I^{FF}) + r_I\,[\pi_I^{SS}(C) - \pi_I^{FS}]$$
$$(\exp[r_E K_E] - 1)] - r_E K_E)/r_I. \tag{7}$$

Recalling that $R_I(C) \equiv r_I\,[\pi_I^{SF}(C) - \pi_I^{FF}]$ and $R_I^c(C) \equiv r_I\,[\pi_I^{SS}(C) - \pi_I^{FS}]$, and substituting above yields, after a bit of algebra:

$$K_I(K_E) = (\ln\,[R_I(C) + R_I^c(C)\,(\exp[r_E K_E] - 1)] - r_E K_E)/r_I.$$

Thus the first order condition results in $K_I(K_E) > 0$ iff $R_I(C) + R_I^c(C)\,(\exp[r_E K_E] - 1) > \exp(r_E K_E)$.

Proof of Theorem 1. Consider the case where $C \leq C_H$. By Assumption (A8), it follows that $\pi_I^{SS}(C) = \pi_I^{FS}$ and $\pi_E^{SS}(C) = \pi_E^{FS}$, giving $R_I^c(C) = 0$ and $R_E^c(C) = R_E$. By Lemma 1, the entrant's investment is $K_E = 0$. Again by Lemma 1, this leads to a simplification of the incumbent's optimal response function as follows: $K_I = [(\ln R_I(C)]/r_I$ if $R_I(C) > 1$, and $K_I = 0$ otherwise.

[1]The authors acknowledge helpful comments and feedback from the Senior Editor and *M&SOM* reviewers, and from members of the Operations, Information, and Technology group at the Stanford Business School.

The probabilities of success are found by plugging the above results for K_I and K_E into Equations (1) and (2), giving: $P_E = 0$, and $P_I = 1 - 1/R_I(C)$ if $R_I(C) > 1$, and $P_I = 0$ otherwise.

The expected profits are found by plugging the above results for K_I and K_E into (5) and (6), giving: $\Pi_E = 0$, and $\Pi_I = \pi_I^{SF}(C) - [1 + \ln R_I(C)]/r_I$ if $R_I(C) > 1$, and $\Pi_I = \pi_I^{FF}$ otherwise.

The case where $C > C_H$ follows similarly.

Proof of Theorem 2. Working directly with the definitions, it is useful to note that $R = R_I(C)\, R_H(C)/R_E$ and

$$R_H(C) \equiv R_h(C)[1 + (R_E - 1)\,(R_I^c(C)/R_I(C))].$$

Consider the case where $C > C_H$. By Assumption (A8), it follows that $\pi_E^{SS}(C) = 0$, giving $R_E^c(C) = 0$. Accordingly, the entrant's optimal response function, given by Lemma 1, simplifies as follows:

$$K_E(K_I) = \begin{cases} [(\ln R_E) - r_I K_I]/r_E & \text{if } R_E > \exp(r_I K_I), \\ 0 & \text{otherwise.} \end{cases}$$

First consider the case where $R_E > \exp(r_I\, K_I)$, indicating the entrant invests. Plugging the above expression for $K_E(K_I)$ into the expression for the incumbent's response function as given in Lemma 1, we obtain (after algebraic manipulation) the incumbent's investment amount for the case where Both Invest is:

$$K_I = (\ln [R_E R_I^c(C)/R_A(C)])/r_I,$$

provided that quantity is positive. Plugging that expression for K_I back into the expression for $K_E(K_I)$, as given in the preceding step, yields (after algebraic manipulation):

$$K_E = (\ln [R_A(C)/R_I^c(C)])/r_E.$$

Thus, provided that both investment quantities are strictly positive, we have found a pure strategy equilibrium with both firms investing. In this equilibrium, $K_I > 0$ holds iff $R_E\, R_I^c(C) > R_A(C)$ which, after some algebra, can be expressed equivalently as $R > R_h(C)$. Similarly, $K_E > 0$ holds iff $R_A(C) > R_I^c(C)$, which can be expressed equivalently as $R < R_H(C)$. Reversing the logic, if $C > C_H$ and $R_h(C) < R < R_H(C)$, then there is a pure strategy equilibrium in which both firms invest strictly positive amounts, as given above, and in Theorem 2. The probabilities of success are found by plugging the above results for K_I and K_E into Equations (1) and (2), giving: $P_I = 1 - R_A(C)/[R_E\, R_I^c(C)]$, and $P_E = 1 - R_I^c(C)/R_A(C)$.

The expected profits are found by plugging the above results for K_I and K_E into (5) and (6):

$$\Pi_I = [-R_A(C) + R_E\, \pi_I^{SS}(C)\, r_I + r_I^2\, (\pi_I^{FF}\, \pi_I^{SS}(C) - \pi_I^{SF}(C)\, \pi_I^{FS}$$
$$- R_A(C) \ln R_E + R_A(C) \ln[R_A(C)/R_I^c(C)])]/[R_A(C) r_I],$$
$$\Pi_E = (R_E - R_I(C) - R_I^c(C) \ln [R_A(C)/R_I^c(C)])/[R_I^c(C) r_E].$$

The other cases follow similarly. (See Schmidt (1998) for details.) Once all cases are complete, it then follows that the pure strategy equilibria found are unique: The several cases considered are mutually exclusive and collectively exhaustive, and for each case there is an equivalent condition on who invests and how much. These conditions together are mutually exclusive and collectively exhaustive as well. That is, there cannot be another combination of who invests what and how much that holds under any of the cases considered.

Proof of Theorem 3. By Theorem 2 the incumbent's profit in the contingent retrenchment region is $\Pi_I = \pi_I^{FS} + [\pi_I^{SF}(C) - \pi_I^{FS}]/R_E - [1 + \ln (R_I(C)/R_E)]/r_I$, and the incumbent's profit in the domination region is $\Pi_I = \pi_I^{SF}(C) - (1 + \ln R_I(C))/r_I$. Of the parameters within these equations, only $\pi_I^{SF}(C)$ and $R_I(C)$ are functions of C. Let $\pi_I^{SF\text{-}CR}(C)$ and $R_I^{CR}(C)$ denote values on the contingent retrenchment side of the crossover point, and let $\pi_I^{SF\text{-}D}(C)$ and $R_I^D(C)$ denote values on the domination side. Note that $\pi_I^{SF\text{-}D}(C) \geq \pi_I^{SF\text{-}CR}(C)$ and $R_I^D(C) \geq R_I^{CR}(C) \geq R_E > 1$, the last weak inequality following from $R \geq R_H(C)$, which holds in both regions, and the strict inequality a paper-wide assumption. The incumbent's profit jump in going from contingent retrenchment to domination is:

$$\begin{aligned}
&[\pi_I^{SF\text{-}D}(C) - (1 + \ln R_I^D(C))/r_I] \\
&\quad - [\pi_I^{FS} + (\pi_I^{SF\text{-}CR}(C) - \pi_I^{FS})/R_E - [1 + \ln (R_I^{CR}(C)/R_E)]/r_I] \\
&\quad = [\pi_I^{SF\text{-}D}(C) - \pi_I^{SF\text{-}CR}(C) + (\pi_I^{SF\text{-}CR}(C) - \pi_I^{FS})(1 - 1/R_E) \\
&\quad + 1/r_I(\ln R_I^{CR}(C) - \ln R_I^D(C) - \ln R_E).
\end{aligned}$$

The objective is to show the profit jump is strictly positive. This will be shown by showing that the profit jump multiplied by r_I is strictly positive:

$$\begin{aligned}
&r_I\, [\pi_I^{SF\text{-}D}(C) - \pi_I^{SF\text{-}CR}(C) + (\pi_I^{SF\text{-}CR}(C) - \pi_I^{FS})(1 - 1/R_E)] \\
&\quad + \ln R_I^{CR}(C) - \ln R_I^D(C) - \ln R_E \\
&\quad = r_I\, (\pi_I^{SF\text{-}D}(C) - \pi_I^{FF}) - r_I(\pi_I^{SF\text{-}CR}(C) - \pi_I^{FF}) \\
&\quad + r_I(\pi_I^{SF\text{-}CR}(C) - \pi_I^{FS})(1 - 1/R_E) \\
&\quad + \ln R_I^{CR}(C) - \ln R_I^D(C) - \ln R_E \quad \text{(add and subtract } r_I\, \pi_I^{FF}) \\
&\quad = (R_I^D(C) - \ln R_I^D(C)) - (R_I^{CR}(C) - \ln R_I^{CR}(C)) \\
&\quad + r_I(\pi_I^{SF\text{-}CR}(C) - \pi_I^{FS})\,(1 - 1/R_E) - \ln R_E \\
&\quad \geq r_I(\pi_I^{SF\text{-}CR}(C) - \pi_I^{FS})(1 - 1/R_E) - \ln R_E \\
&\quad \geq R_I\, (\pi_I^{SF\text{-}CR}(C) - \pi_I^{FF})(1 - 1/R_E) - \ln R_E \\
&\qquad \text{(since } \pi_I^{FF} \geq \pi_I^{FS}\text{, by Assumption A6)} \\
&\quad = R_I^{CR}(C)\,(1 - 1/R_E) - \ln R_E \\
&\quad \geq R_E\,(1 - 1/R_E) - \ln R_E \ \text{(since } R_I^{CR}(C) \geq R_E) \\
&\quad = R_E - 1 - \ln R_E \\
&\quad > 0.
\end{aligned}$$

The first inequality follows from $f(x) = x - \ln(x)$ being an increasing function of x for $x \geq 1$. (Use the fact that $R_I^D(C) \geq R_I^{CR}(C)$.) Furthermore, $f(x) > 1$ for $R_E > 1$, which yields the last inequality, since $R_E > 1$.

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