Tying, investment, and the dynamic leverage theory

Jay Pil Choi*
Christodoulos Stefanadis**

The idea that an incumbent supplier may tie two complementary products to fend off potential entrants is popular among practitioners yet is not fully understood in formal economic theory. This paper makes sense of the argument by formally deriving a dynamic version of the old leverage doctrine. It is shown that when an incumbent monopolist faces the threat of entry in all complementary components, tying may make the prospects of successful entry less certain, discouraging rivals from investing and innovating. Tie-in sales may reduce consumer and total economic welfare.

* Department of Economics, Michigan State University, East Lansing, MI 48824, tel. (517) 353 7281, e-mail: choi@bus.msu.edu.
** Payment Studies, Research Department., Federal Reserve Bank of New York, 33 Liberty Street, New York, NY 10045-0001, tel. (212) 720 6178, e-mail: chris.stefanadis@ny.frb.org.

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1. Introduction

In recent years, tying in the high-technology sector has been one of the hottest issues in antitrust economics. When, for example, practitioners try to explain the extraordinary success of Microsoft, they often stress the use of tie-in sales as a defense against entrants. By tying complementary products to its PC operating system, Microsoft allegedly creates an “applications barrier to entry,” fending off potential competitors. Still, tying as a barrier to entry is not fully understood in terms of formal economic theory.

This paper develops a simple formal model that illustrates how tying can impact the investment incentives of entrants, buttressing an incumbent’s monopoly position. The crucial ingredient of the model is the presence of a risky up-front R&D investment. A potential entrant can enter the market if it succeeds in innovation and obtains a superior technology; the probability of success depends on the level of its R&D expenditures. In this framework, the tying of two complementary components by a monopolist credibly makes entry in one component completely dependent upon success in the other. An entrant can gain access to consumers and earn a positive profit only if the entrant in the other product is also successful. Tying, thus, makes the prospects of investment less certain, reducing the entrants’ incentive for investment and innovation.

In essence, the incumbent faces the following trade-off when it makes its tying decision. If only one entrant succeeds, the incumbent can use its monopoly position in the other component to practice a “price squeeze,” capturing a share in the value of the entrant’s innovation. If both entrants innovate, however, the incumbent is forced out of the market. Tying is a profitable strategy when the incumbent’s risk of being supplanted by low-cost entry in both components dominates the benefits of entry in a single component. In this case, tying may reduce consumer and total economic welfare.

The same reasoning applies when the model is extended so that the incumbent firm also has the opportunity to upgrade its know-how by investing in new technologies. Then, aside from strengthening the incumbent's monopoly position, tying may also improve the incumbent's standing in the technological competition with the entrants.

An important aspect of our argument is the irreversibility of the tying decision. Commitment to tying can be made, for example, through technological arrangements in the production process or in product design. If, on the other hand, precommitment is not credible, the incumbent may find the tying decision suboptimal ex post: when only one entrant succeeds in innovation, the incumbent will untie its two components to practice a price squeeze. Precommitment to tying is, thus, necessary for the incumbent to impact the entrants' investment incentives.[1]

On an empirical level, the model is mainly applicable to risky and dynamic industries where the primary mode of entry is via innovation with substantial investment costs. The high-tech sector, which often requires large amounts of up-front R&D spending, is a good example. For instance, the model has potential applications to the ongoing *United States v. Microsoft*.[2]

One of the charges brought against Microsoft is that it ties technologically its operating system to a complementary product, the Internet Explorer. Although Microsoft has a dominant position in both the PC operating systems and the Internet browser market, it faces potential competition in both components.[3] Specifically, a new programming language, Java, has started to challenge Microsoft's position in operating systems. Java is designed to permit applications written in it to run, without change, on any kind of operating system. Also, Microsoft faces competition in Internet browsers from the Netscape Navigator. Java and Internet browsers are complementary components used in conjunction with one another: Internet browsers are the most significant distribution vehicle of Java to end users.

By tying its operating system to its Internet Explorer, Microsoft makes entry in one component dependent upon success in the other: Netscape can gain access to consumers and earn a significant profit mainly if Java succeeds, and vice versa. Tying may, thus, make the prospects of investment in the Netscape Navigator, or Java more uncertain, reducing these rivals' incentive for innovation.[4]

The general idea that it is more difficult for a rival to match an array of interlocked activities than to imitate an individual process is informally discussed in the management literature (Porter, 1996). As Porter points out, "positions built on systems of activities are far more sustainable than those built on individual activities."[5] This paper develops a simple model that draws out and formalizes the implications of this general idea for tying.

In the law literature, the old leverage theory of tying informally states that a firm with monopoly power in one market has an incentive to monopolize complementary markets as well. The firm can leverage its power from the primary industry to complementary industries, earning extra monopoly profits. Despite its informal nature, the leverage theory has been the basis of several court decisions (e.g., *Terminal Railroad Association*, *IBM*, *Standard Oil*, *Civil Aeronautics Board* hearings).[6]

Formal economic theory, on the other hand, has cast serious doubt about the validity of the leverage doctrine. In particular, the Chicago School (e.g., Director and Levi, 1956; Bowman, 1957; Posner, 1976; Bork, 1978) argues that when two components are used in conjunction with one another, there is only one final product, and, thus, only one monopoly power to be exploited. A monopolist in one component can extract the entire monopoly rent without foreclosing sales in complementary components.[7] Accordingly, when a monopolist practices tying, its motivation cannot be leverage. Instead, the Chicago School points to a number of efficiency justifications, or benign explanations (e.g., price discrimination) for tie-in sales. As Bork (1978) points out, "[the leverage theory of tying] is merely another example of the discredited transfer-of-power theory, and perhaps no other variety of that theory has been so thoroughly and repeatedly demolished in the legal and economic literature."[8]

There is no doubt that the Chicago School view is applicable to numerous situations. Under certain circumstances, tying can indeed be attributed to efficiency reasons. Nevertheless, this paper shows that when the assumptions of the Chicago benchmark model are modified to reflect market conditions in risky and dynamic industries, the validity of the leverage theory can be restored.

There are three key differences between the Chicago fixed sum argument and this model. First, in our model, the incumbent firm is not a pure monopolist, but rather faces the threat of potential entry in all components (even if entry is highly unlikely in some components). As Rey and Tirole (1996) point out, in practice, bottlenecks are rarely pure bottlenecks; they most often encounter potential competition. Secondly, the incumbent in our model initially has a monopoly position in both complementary components. The Chicago School, on the other hand, examines how an incumbent can leverage its power from a monopolized to a competitive industry. The third important difference is our focus on the role of risky investment. On the basis of these assumptions, our model arrives at a new, more dynamic version of the old leverage doctrine with a special emphasis on incentives to innovate.

In the leverage theory literature, Whinston (1990) and Carlton and Waldman (1998) also point out that tying may foreclose competition. More specifically, Whinston (1990) demonstrates that tying a monopolized primary product to an unrelated differentiated product may allow the extension of monopoly power to the differentiated market as well. Tying may be profitable because it allows the monopolist to commit to a more aggressive pricing strategy, blocking the entry of rivals in the differentiated market.[9] Whinston places emphasis on the tying of unrelated, rather than complementary products. In the case of complementary components, on the other hand, he concludes that tying does not take place, except in the rather special setting where there is either an unrelated use of one component, or an inferior, competitive alternative. Unlike Whinston, we focus on the tying of complementary components and show that tying can be used to defend the incumbent's position in both the primary and the complementary market.

Carlton and Waldman (1998) examine the role of “intertemporal economies of scope” in entry deterrence. In their two-period model, the monopolist is the sole producer in the primary market in period 1, while there is potential for entry in period 2. In the complementary market, on the other hand, there is potential for immediate entry. By tying the complementary to the primary component, the monopolist keeps its rival out of the complementary market in period 1, which, in turn, may make entry into the primary market in period 2 unprofitable. The reason is that the fixed cost of entry for the complementary good creates intertemporal economies of scope: the rival firm may not be able to recoup its entry cost in the complementary market by operating in one period only. It is, thus, less profitable for a rival to enter the primary market in period 2 when entry requires entering both markets, rather than one. This may allow the incumbent monopolist to extract a monopoly rent in both periods. Unlike Carlton and Waldman, who explore the role of intertemporal economies of scope, we focus on the probabilistic nature of R&D investment and illustrate how tying can be strategically used to impact R&D, or investment incentives. We show that tying leads to greater uncertainty, discouraging investment and innovation.

Farrell and Katz (forthcoming) develop a related model of systems markets where innovation incentives are analyzed. In the model, there is a single producer of component A, firm M, and several independent suppliers of a complementary component B. Farrell and Katz show that M’s vertical integration into the market for B enhances its ability to extract efficiency rents through an “investment squeeze,” or a “price squeeze.” When M integrates into B, it has excessive incentives to innovate in order to force the independent suppliers of B to charge lower prices than they otherwise would. Unlike Farrell and Katz, who focus on the effects of vertical integration, we examine the impact of tying and exclusion; in the presence of tying, the incumbent’s components are not available separately. Furthermore, in our model, the incumbent also faces the threat of entry in component A (as in Carlton and Waldman, 1998); tying may, thus, allow the incumbent to preserve its monopoly position in both components.

Rey and Tirole (1996) and Economides (1998) examine a rent shifting rationale for tying. They show that an upstream bottleneck monopolist may raise the costs of downstream rivals to allow its downstream division to earn higher profits. Rey and Tirole (1996) also show that a patent holder may have an incentive to practice tying to prevent rent dissipation. When downstream firms pay a fixed sum to purchase a license, the amount they are willing to pay is low when there is intense downstream competition. In these circumstances, tying may be a commitment strategy that prevents the patent holder from granting an excessive number of licenses.[10]

The paper consists of five sections. Section 2 presents the basic model and examines the equilibrium of the model. Section 3 explores the possibility of an integrated entrant. Section 4 extends the basic model to allow for the possibility of investment by the incumbent firm. Finally, section 5 contains concluding remarks.

2. The basic model

Firm 1 is the incumbent monopolist for two complementary components, A and B, that are valuable only when used together. Consumers combine A and B in fixed proportions on a one to one basis to form a final product. Firm 1 has already incurred a fixed cost of entry and now only faces a constant marginal cost $\bar{c}$ for each component. We refer to components A and B, when produced by firm 1, as A1 and B1. There are n identical consumers that have unit demands; each consumes either one or zero unit of the final product. Also, a consumer derives a value from consumption equal to V.

Firms A2 and B2 are potential entrants in the market for components A and B respectively. A2 and B2 are separate firms. In section 3, an alternative model will be examined in which A2 and B2 are integrated. As we will see, the outcome of the game will be similar.

We consider a dynamic industry where innovation serves as the primary vehicle for successful entry. To incorporate this aspect, we assume that a potential entrant has the opportunity to make an up-front investment (e.g., an R&D investment) to enter the market. An entrant has access to a new, low-cost technology, which is superior to the incumbent's know-how.[11] However, the outcome of the R&D investment is uncertain, in that the investment can either succeed, or fail. In the former case, the entrant's marginal cost is $\underline{c}$, where $\underline{c} < \bar{c}$. If the investment fails, on the other hand, the entrant's cost is higher than V and entry is not profitable. Consumers view the components produced by the monopolist and the entrants as perfect substitutes for each other.[12]

Components A2 and B2 are symmetric in that they entail an identical probability function. The probabilities of success for the entrants are $p(I_{A2})$ and $p(I_{B2})$, where I_{A2} and I_{B2} are the R&D investment expenditures of A2 and B2 respectively. The probability function is increasing in the amount of the R&D investment but at a decreasing rate, i.e., $p'(I) > 0$ and $p''(I) < 0$. The concavity of the probability function ensures the existence of equilibrium in the investment stage game by implying that each entrant's profit function is concave in its own action. We further assume that

$$p''(I_{A2})\, p''(I_{B2})\, p(I_{A2})p(I_{B2}) - [p'(I_{A2})p'(I_{B2})]^2 > 0. \qquad (1)$$

Condition (1) ensures global stability and uniqueness of equilibrium in the investment stage game.[13]

Before A2 and B2 make their R&D investments, firm 1 has the opportunity to tie its two components. If tied, the sale of component A1 is made contingent upon the sale of component B1 and vice versa; A1 and B1 are not available separately. A tying decision is binding for the entire game. As in Whinston (1990) and Carbajo, De Meza, and Seidman (1990), we assume that this precommitment is made possible through technological arrangements in the production process or in product design.[14] Our timing assumption reflects the fact that the tying decision through product design is a long-term decision that cannot be modified easily.

In summary, we have a three-stage game:

Stage 1: Firm 1 decides whether to tie A1 and B1.

Stage 2: Investment decisions by A2 and B2.

Stage 3: Price competition.

For simplicity, we adopt the standard tie-breaking convention that if a consumer is indifferent between buying from the incumbent and an entrant, it will buy from the low-cost supplier.[15]

To solve for the equilibrium of this model, we proceed by backward induction.

Price competition

The (fixed proportions) complementarity between A and B implies that the two markets cannot be analyzed independently even in the absence of tying. As a result, Bertrand competition may yield multiple price equilibria when there is entry into only one component market.

Consider the case of no tying in which only one potential entrant, A2 or B2, succeeds in its investment. In this case, we have multiple price equilibria, which correspond to different distributions of the value created by innovation, $S = n(\bar{c} - \underline{c})$, between the incumbent and the entrant. When, for instance, only entrant A2 succeeds, one equilibrium is that firm 1 (the incumbent) charges prices $\bar{c}$ and $(V - \bar{c})$ for components A and B respectively, while A2 (the entrant) sets its price equal to $\bar{c}$. In this equilibrium, the entrant captures the entire surplus S from its innovation. However, in another equilibrium, the incumbent charges prices $\underline{c}$ and $(V - \underline{c})$ for components A and B respectively, while A2 sets its price equal to $\underline{c}$. In this equilibrium, the incumbent practices a perfect price squeeze, taking advantage of its position as the sole supplier of complementary component B and extracting the entire surplus created by the entrant's innovation (Ordover, Sykes, and Willig, 1985).

There is a wide range of equilibria between these two polar cases, representing different distributions of the surplus created by innovation between the two parties. Any distribution can be sustained as equilibrium, depending on the degree of price squeeze practiced by the incumbent. In particular, when only entrant A2 succeeds, the range of component A's equilibrium price is $x_{A1} = x_{A2} = x_A \in [\underline{c}, \bar{c}]$ with corresponding B1's equilibrium price $x_{B1} = V - x_A$.

We assume that when only one potential entrant succeeds in its investment, a share l of the cost savings S is captured by the incumbent, while a share $1 - l$ is captured by the entrant, where $0 \leq l \leq 1$. Thus, l serves as a parameter for the degree of price squeeze exercised by the incumbent.[16] It follows that when only A2 succeeds, equilibrium prices in each component market are $x_{A1} = x_{A2} = x_A = \underline{c} + (1 - l)(\bar{c} - \underline{c})$ and $x_{B1} = V - \underline{c} - (1 - l)(\bar{c} - \underline{c})$.

Now consider the case of tying. When only one firm, say A2, succeeds in innovation, A2 is not able to sell its product to consumers because B1 is not available separately. Thus, in the tying case, an entrant has access to consumers only when both A2 and B2 succeed in innovation. In the tying case, when both entrants succeed, there are also multiple equilibria in price competition. More precisely, any price combination of x_{A2} and x_{B2} such that $x_{A2} + x_{B2} = 2\bar{c}$ and $x_{A2} \geq \underline{c}$, $x_{B2} \geq \underline{c}$ can be sustained as an equilibrium, whereas the incumbent charges a price $2\bar{c}$ for the bundled product. In this case, we focus on the unique symmetric equilibrium, in which each entrant obtains the full reward for its innovation, i.e., equilibrium prices are $x_{A2} = \bar{c}$ and $x_{B2} = \bar{c}$.

Investment decisions

No tying. Let us first assume that firm 1 does not tie A1 and B1 in stage 1. Then, if A2 succeeds in its R&D investment in stage 2, its profit will depend on whether B2 also succeeds in its R&D investment. More precisely, A2 will earn a stage 3 operating profit – a profit excluding its R&D investment – equal to $S = n(\bar{c} - \underline{c})$ if B2 also succeeds, or equal to $(1 - l)S = (1 - l)n(\bar{c} - \underline{c})$ if B2 fails. Thus, in stage 2, A2 faces the following maximization problem:

$$\max_{\{I_{A2}\}} \Pi_{A2} = p(I_{A2})[1 - p(I_{B2})](1 - l)S + p(I_{A2})p(I_{B2})S - I_{A2}. \tag{2}$$

The first-order condition for the maximization problem is given by

$$p'(I_{A2}) = \frac{1}{[1 - l + lp(I_{B2})]S}. \tag{3}$$

Similarly B2's maximization problem yields:

$$p'(I_{B2}) = \frac{1}{[1 - l + lp(I_{A2})]S}. \tag{4}$$

The equilibrium levels of investment under no tying, $I_{A2}*$ and $I_{B2}*$ can be derived by solving equations (3) and (4) simultaneously. Given that the model is symmetric and the condition for global stability is met, we have $I_{A2}* = I_{B2}* = I*$.[17] Thus, in equilibrium

$$p'(I*) = \frac{1}{[1 - l + lp(I*)]S}. \tag{5}$$

We can perform a comparative static analysis of how the degree of price squeeze l by the incumbent affects the equilibrium levels of investment I^* by the potential entrants. By totally differentiating the first-order condition (5), with the argument of p(.) suppressed, we have

$$[p''(1 - l + lp)S + l(p')^2S]dI^* - p'(1 - p)S\,dl = 0. \tag{6}$$

Rearranging terms in equation (6) gives

$$\frac{dI^*}{dl} = \frac{p'(1-p)}{[p''p + (p')^2]l + (1-l)p''}. \tag{7}$$

The denominator of (7) is negative due to condition (1).[18] As a result, we have $\frac{dI^*}{dl} < 0$. We draw the natural conclusion that the more profit the incumbent can extract from an entrant's innovation, the weaker the entrant's incentives to conduct R&D.

Tying. Suppose now that firm 1 ties A1 and B1 in stage 1. Then, A2 will earn a strictly positive operating profit in the pricing stage only if both A2 and B2 succeed in their fixed investment in stage 2. If A2 succeeds and B2 fails, A2 will not be able to sell its component to consumers since B1 is not available separately. A2's profit maximization problem becomes:

$$\underset{\{I_{A2}\}}{\text{Max}}\ \tilde{\Pi}_{A2} = p(I_{A2})p(I_{B2})S - I_{A2}. \tag{8}$$

With tying, the first-order condition for A2's maximization problem is given by

$$p'(I_{A2}) = \frac{1}{p(I_{B2})S}\,. \tag{9}$$

Similarly, B2's maximization problem becomes:

$$p'(I_{B2}) = \frac{1}{p(I_{A2})S}\,. \tag{10}$$

The equilibrium levels of investment under tying, $\tilde{I}_{A2}*$ and $\tilde{I}_{B2}*$ can be derived by solving equations (9) and (10) simultaneously.[19] As in the case of no tying, the symmetry of the model and the condition for global stability imply that $\tilde{I}_{A2}* = \tilde{I}_{B2}* = \tilde{I}*$.[20] Thus, in equilibrium

$$p'(\tilde{I}*) = \frac{1}{p(\tilde{I}*)S}\,. \tag{11}$$

Effects of Tying. To analyze the effects of tying on R&D investment, we first observe that from the perspective of *potential entrants*, tying is equivalent to the case of a perfect price squeeze without tying. That is, when we write the investment level of entrants in the absence of tying as $I*(l)$, we have $I*(l = 1) = \tilde{I}*$. This can be seen by comparing the objective functions (8) and (2) while setting $l = 1$. In both cases, entry into only one component generates zero profits for the entrant. Thus, the equilibrium investment level is the same across regimes when $l = 1$.

We also know that $I*(l)$ is a decreasing function of l. Taken together, we conclude that when A1 and B1 are tied, A2's and B2's equilibrium levels of R&D investment are reduced, leading to lower probabilities of success $p(I_{A2})$ and $p(I_{B2})$. On an intuitive level, tying makes the prospects of a potential entrant's investment completely contingent on the other firm's success, lowering the probability that the entrant will eventually earn a profit. Thus, tying reduces A2's and B2's incentive for fixed investment.

Proposition 1: When the incumbent practices tying, the entrants' R&D investment decreases, leading to a lower probability of entry in each market.

Tying decisions

An incumbent supplying two complementary components of a product can discourage the R&D efforts of entrants by tying the components together. In doing so, it gives up the prospective benefit of innovation in a single component, but this may be outweighed by the reduced risk of being supplanted by low-cost entry into both components. In essence, the tying decision hinges on these two opposing effects on the incumbent's expected profit.

Specifically, in the absence of tying, the incumbent's expected profit depends on l and can be written as

$$\Pi_1^*(l) = [1 - p(I^*(l))^2]n(V - 2\bar{c}) + 2p(I^*(l))[1 - p(I^*(l))]lS. \tag{12}$$

If, on the other hand, the incumbent ties, its expected profit is independent of l and can be written as

$$\tilde{\Pi}_1^* = [1 - p(\tilde{I}^*)^2]n(V - 2\bar{c}). \tag{13}$$

Let us define $D(l)$ as the changes in the expected profit due to tying:

$$D(l) = \tilde{\Pi}_1^* - \Pi_1^*(l)$$

$$= [p(I^*(l))^2 - p(\tilde{I}^*)^2]n(V - 2\bar{c}) - 2p(I^*(l))[1 - p(I^*(l))]lS. \qquad (14)$$

The changes in the incumbent's expected profit can be decomposed into two opposing effects.

(a) *Displacement Effect*: When both A2 and B2 succeed in their R&D investment, the incumbent is displaced by the new entrant with the incumbent's profit driven to zero. Tying lowers the probability of this event from $p(I^*(l))^2$ to $p(\tilde{I}^*)^2$. This effect is *positive* and is given by the first term in (14), i.e., $[p(I^*(l))^2 - p(\tilde{I}^*)^2]n(V - 2\bar{c}) \geq 0$.

(b) *Price Squeeze Effect with Partial Entry*: In the absence of tying, when only one entrant, A2 or B2, innovates, the incumbent obtains a share l of the realized cost savings S. Tying, on the other hand, prevents the incumbent from capturing any share of the value created by the entrant's innovation. This effect is *negative* and is represented by the second term in (14), i.e., $-2p(I^*(l))[1 - p(I^*(l))]lS \leq 0$.

Needless to say, firm 1 decides to tie when $D(l) > 0$, that is, when the positive effect dominates the negative effect.

Notice that $D(l = 0) > 0$. The reason is that when $l = 0$, the incumbent cannot extract any surplus from low-cost entry into a single component even in the absence of tying. Thus, the price squeeze effect of tying is nonexistent and tying has only a positive effect on the profit of the incumbent firm. In the other extreme case of $l = 1$, in contrast, we have $D(l = 1) < 0$. The reason is that when $l = 1$, the equilibrium investment levels are the same across regimes; $I^*(l = 1) = \tilde{I}^*$. Thus, there is no positive effect of reducing the probability of displacement. Since $D(l)$ is a continuous function in l, there exist $l \in (0,1)$ such that $D(l) = 0$. Let l^* be the smallest l such that $D(l) = 0$.[21] Then, $D(l) > 0$ for all $l \in [0, l^*)$. That is, firm 1 chooses to tie at least for a range of l which is less than l^*.

Proposition 2: $\exists\, l^* \in (0,1)$ such that firm 1 ties A1 and B1 in stage 1 $\forall\, l \in [0, l^*)$.

The idea is that firm 1 can discourage potential entrants from investing by practicing tying. In doing so, it loses out on the prospective benefit of innovation in a single component, but this may be offset by the reduced risk of being superseded by low-cost entry into both components. When l is small, the ability of the incumbent to extract surplus from low-cost entry into a single component is limited. Thus, the concern to reduce the risk of entry into both components outweighs the loss of profit in the case of partial entry.

An important point to notice is that our results depend on commitment. When precommitment to tying is not credible, the entrants' incentives for investment are not reduced: once one entrant enters the market, firm 1 may be inclined to untie A1 and B1 to obtain its share l of the value S created by innovation. Thus, for our argument to hold, the incumbent must demonstrate its commitment to tying convincingly. For example, firm 1 can be convincing by practicing technological tying, so that the cost of untying is very high.

Welfare analysis

A social planner seeking to increase total economic welfare would have to maximize $p(I_{A2})S - I_{A2} + p(I_{B2})S - I_{B2}$ with respect to I_{A2} and I_{B2}. The welfare maximization conditions would, thus, be $p'(I_{A2}) = p'(I_{B2}) = 1/S$. Since $\frac{1}{S} \leq \frac{1}{[(1 - l + l p(I)]S}$, the social planner's investment would be higher than that of potential entrants even in the absence of tying. A2 and

B2 underinvest from a social welfare standpoint because they do not take into account the potential benefit of innovation lS to the incumbent.[22] By reducing A2's and B2's incentives for fixed investment even further, tying leads to lower total economic welfare. Furthermore, tying entails a second inefficiency. When only one entrant succeeds in innovation, it cannot market its low-cost product because it does not have access to the complementary component.

In both the tying and the no tying cases, consumer surplus is zero unless both A2 and B2 succeed in their investment, in which case consumer surplus becomes $n(V - 2\bar{c})$. Since tying lowers the probabilities of success ($p(\tilde{I}^*) \leq p(I^*(l))$), it also reduces consumer welfare.

Proposition 3: Tying lowers consumer and total economic welfare.

3. Integrated entrant

The basic model assumes that A2 and B2 are two independent firms. We will now examine a game in which A2 and B2 are an integrated firm, which we call firm 2. As we will see, the results will be basically similar.

We assume that condition (1) still holds, so that the profit function of firm 2 in the investment stage is globally concave.[23] In the no tying case, firm 2 faces the following maximization problem:

$$\underset{\{I_{A2},\, I_{B2}\}}{\text{Max}}\ \Pi_2 = [p(I_{A2})(1 - p(I_{B2}) + p(I_{B2})(1 - p(I_{A2}))](1 - l)S + 2p(I_{A2})\mathrm{p}(I_{B2})S - I_{A2} - I_{B2}\,. \qquad (15)$$

The first-order conditions are given by:

$$p'(I_{A2}) = \frac{1}{[1 - l + 2lp(I_{B2})]S}, \tag{16a}$$

$$p'(I_{B2}) = \frac{1}{[1 - l + 2lp(I_{A2})]S}. \tag{16b}$$

The equilibrium levels of investment under no tying, $I_{A2}*$ and $I_{B2}*$ can be derived by solving equations (16a) and (16b) simultaneously. Given that the model is symmetric and the condition for global concavity is met, we have $I_{A2}* = I_{B2}* = I*$. Thus, in equilibrium

$$p'(I*) = \frac{1}{[1 - l + 2lp(I*)]S}. \tag{17}$$

In the tying case, on the other hand, firm 2's profit maximization problem becomes:

$$\max_{\{I_{A2},\, I_{B2}\}} \tilde{\Pi}_2 = 2p(I_{A2})\mathrm{p}(I_{B2})S - I_{A2} - I_{B2}. \tag{18}$$

The first-order conditions under tying are:

$$p'(I_{A2}) = \frac{1}{2p(I_{B2})S}, \tag{19a}$$

$$p'(I_{B2}) = \frac{1}{2p(I_{A2})S}. \tag{19b}$$

So, in the tying equilibrium, we have $\tilde{\mathrm{I}}_{\mathrm{A2}}* = \tilde{\mathrm{I}}_{\mathrm{B2}}* = \tilde{\mathrm{I}}*$, where

$$p'(\tilde{I}^*) = \frac{1}{2p(\tilde{I}^*)S}. \qquad (20)$$

The effects of tying

As in the basic model of section 2.2, comparison of (17) and (20) once again reveals that from the perspective of the *integrated potential entrant*, tying is equivalent to the case of a perfect price squeeze without tying, i.e., $I^*(l = 1) = \tilde{I}^*$. To analyze how parameter l affects the equilibrium level of investment by the integrated entrant, we totally differentiate the first order condition (17) with the argument of p(.) suppressed:

$$[p''(1 - l + 2lp)S + 2l(p')^2 S]dI^* - p'(1 - 2p)Sdl = 0. \qquad (21)$$

Rearranging terms in Eq. (21) gives us

$$\frac{dI^*}{dl} = \frac{p'(1-2p)}{2[p''p + (p')^2]l + (1-l)p''}. \qquad (22)$$

Once again, the denominator of (22) is negative due to condition (1). As a result, we have $\frac{dI^*}{dl} <$ 0 if and only if $p(I^*) < 1/2$. This implies that when A1 and B1 are tied, A2's and B2's equilibrium levels of fixed investment are reduced if $p(I^*) < 1/2$.

The reason we need the condition $p(I^*) < 1/2$ can be explained by the two opposing effects tying entails for the integrated entrant.

(a) Own Effect: Tying discourages A2 from investing, leading to a lower I_{A2} (for any given level of I_{B2}), because A2 knows that it will not be able to sell its product to consumers unless B2 also succeeds (i.e., $[1 - l + lp(I_{B2})]S > p(I_{B2})S$).

(b) Cross Effect: Tying encourages A2 to invest, leading to a higher I_{A2} (for any given level of I_{B2}), because firm 2 knows that success in A2 will also benefit its other component B2, which cannot be sold unless A2 also succeeds (i.e., $lp(I_{B2})S < p(I_{B2})S$).

The same effects also hold for B2. Tying leads to a lower equilibrium investment by firm 2 when the own effect dominates the cross effect, i.e., when $[1 - l + 2lp(I^*)]S > 2p(I^*)S \Rightarrow p(I^*) < 1/2$. This condition holds if the success probability function $p(.)$ is sufficiently concave.

Proposition 4: When the incumbent firm 1 practices tying, firm 2's R&D investment is reduced ($\tilde{I}^* < I^*$) if the probability of success in each component under no tying is lower than 1/2, i.e., if $p(I^*) < 1/2$.

When the investment is costly and uncertain and, thus, the probability of success under no tying is small (i.e., $p(I^*) < 1/2$), the own effect dominates the cross effect because it is more likely that innovation in the complementary component will fail, whereas uncertainty limits the positive benefits of additional investment to the complementary component.

Tying decisions

As in the basic model, firm 1 chooses to tie when $D(l) = \tilde{\Pi}_1^* - \Pi_1^*(l) = [p(I^*(l))^2 - p(\tilde{I}^*)^2]n(V - 2\bar{c}) - 2p(I^*(l))[1 - p(I^*(l))]lS > 0$. Notice that firm 1 will never practice tying if $p(I^*(l)) \geq 1/2$ because in these circumstances, tying will increase firm 1's risk of being supplanted by low-cost entry in both components ($\tilde{I}^* \geq I^*(l)$), without allowing firm 1 to benefit from innovation in a single component.

However, if $p(I^*(l)) < 1/2$ for all l, a similar line of reasoning as in the basic model leads us to conclude that firm 1 chooses to tie at least for a range of l close to zero. Specifically, $D(l) > 0$ at $l = 0$ whereas $D(l) < 0$ at $l = 1$. Since $D(l)$ is a continuous function in l, we can find $l \in (0,1)$ such that $D(l) = 0$. Let l^{**} be the smallest l such that $D(l) = 0$. Then, $D(l) > 0$, for all $l \in [0, l^{**})$.

Proposition 5: In the case of an integrated potential entrant, if $p(I^*) < 1/2$ for all l, then $\exists\, l^{**} \in (0,1)$ such that firm 1 ties A1 and B1 in stage 1 $\forall \lambda \in [0, l^{**})$.

For $p(I^*(l)) < 1/2$, tying leads to a lower consumer and total economic welfare. The proof is similar to the basic model.

Proposition 6: When firm 1 chooses to tie (i.e., when $\tilde{\Pi}_1^* > \Pi_1^*(l)$) in the case of an integrated entrant, tying leads to lower consumer and total economic welfare.

4. Investment by the incumbent

So far we have assumed that only potential entrants have the opportunity to invest in the new, low-cost technology. The incumbent has already made its fixed investment and cannot improve its know-how. This section extends the model to allow for technological competition, in which all players have the opportunity to invest in the new product. As we will see, most of our results are robust to the introduction of investment by the incumbent.

Specifically, in the game, firm 1 has already incurred a fixed cost of entry and now only faces a constant marginal cost $\bar{c}$ for each component. However, firm 1 also has the opportunity to make an additional R&D investment, attempting to obtain the new technology for each component. The new technology entails a lower marginal cost $\underline{c} < \bar{c}$. As in section 3, firm 2 is a potential entrant in the market for components A and B. If firm 2 succeeds in a component, its marginal cost is $\underline{c} < \bar{c}$. If, on the other hand, it fails, its cost is higher than V.

In stage 2, each firm makes an R&D investment in *basic* research that may lead to innovation in component A or component B. This assumption simplifies the analysis by reducing the number of strategic instruments for each firm to one. The success events are independent across components and firms. Firms 1 and 2 face an identical probability function. Thus, when firm j invests I_j in basic research, it has a probability $p(I_j)$ to obtain the new technology in component Aj, as well as a probability $p(I_j)$ to succeed in Bj (j = 1,2). The probability function in each component is increasing in the amount of the basic R&D investment, i.e., $p'(I) > 0$.

Without tying, there are several possibilities in the pricing stage, depending on the outcome of the R&D stage. When both firms, for example, succeed in both components, prices are driven to marginal cost $\underline{c}$ and firms earn zero profits. If, on the other hand, both firms succeed in only one component, the market outcome depends on whether they succeed in the same or different components. If they succeed in the same component, say A, the incumbent can obtain the entire value of innovation S by practicing a perfect price squeeze in A. Although competition drives the price of component A to $\underline{c}$, the incumbent can obtain the entire surplus S by raising the price of component B to $V - \underline{c}$. If they succeed in different components, the incumbent obtains a surplus $(1+l)S$, that is, a portion l of the value S created by the entrant in addition to the value S created by the incumbent itself. This follows from our earlier assumption on the degree of price squeeze.

In the no tying case, firm 1 thus faces the following maximization problem in stage 2:

$$\underset{\{I_1\}}{\text{Max}}\ \Pi_1 = [1 - p(I_2)^2]n(V - 2\bar{c}) + 2p(I_2)[1 - p(I_2)]\,lS$$

$$+ 2p(I_1)[1 - p(I_2)][1 + (1 - l)p(I_2)]S - I_1. \tag{23}$$

The first-order condition for the maximization problem under no tying is given by

$$p'(I_1) = \frac{1}{2[1 - p(I_2)][1 + (1 - l)p(I_2)]S}. \tag{24}$$

Firm 2's maximization problem is:

$$\underset{\{I_2\}}{\text{Max}}\ \Pi_2 = 2p(I_2)[1 - p(I_1)][1 - l + lp(I_2)]S - I_2. \tag{25}$$

The first-order condition is given by

$$p'(I_2) = \frac{1}{2[1 - p(I_1)][1 - l + 2lp(I_2)]S}. \tag{26}$$

First-order conditions (24) and (26) implicitly define reaction functions $R_1(I_2)$ and $R_2(I_1)$ for firms 1 and 2 respectively. The Nash equilibrium levels of investment under no tying, I_1* and I_2* can be derived by solving equations (24) and (26) simultaneously. To ensure uniqueness and the stability of the equilibrium, we assume that $|\partial^2\Pi_i/\partial I_i^2| > |\partial^2\Pi_i/\partial I_i\partial I_j|$, where i ≠ j.

In the tying case, on the other hand, firm 1's profit maximization problem becomes:

$$\max_{\{I_1\}} \tilde{\Pi}_1 = [1 - p(I_2)^2]n(V - 2\bar{c}) + 2p(I_1)[1 + p(I_2)][1 - p(I_2)]S - I_1. \tag{27}$$

The first-order condition for the maximization problem under tying is given by

$$p'(I_1) = \frac{1}{2[1 - p(I_2)][1 + p(I_2)]S}. \tag{28}$$

Firm 2's maximization problem under firm 1's tying becomes:

$$\max_{\{I_2\}} \tilde{\Pi}_2 = 2p(I_2)^2[1 - p(I_1)]S - I_2. \tag{29}$$

The first-order condition is given by

$$p'(I_2) = \frac{1}{4[1 - p(I_1)]p(I_2)S}. \tag{30}$$

The equilibrium levels of investment under tying, $\tilde{I}_1{}^*$ and $\tilde{I}_2{}^*$ can be derived by solving equations (28) and (30) simultaneously. Once again, we assume that $|\partial^2\tilde{\Pi}_i / \partial I_i^2| > |\partial^2\tilde{\Pi}_i / \partial I_i \partial I_j|$, where i ≠ j to ensure uniqueness and stability of the equilibrium in the tying case. Notice that in both the tying and no tying cases, investment expenditures I_1 and I_2 are strategic substitutes (that is, $\partial^2\Pi_i / \partial I_i \partial I_j < 0$ and $\partial^2\tilde{\Pi}_i / \partial I_i \partial I_j < 0$); investment reaction curves are downward sloping.[24]

The effects of tying

Comparison of the first-order conditions (24) and (28) reveals that when A1 and B1 are tied, firm 1's incentives for R&D investment are strengthened. To understand this, notice that $\dfrac{1}{2[1-p(I_2)][1+(1-l)p(I_2)]S} \geq \dfrac{1}{2[1-p(I_2)][1+p(I_2)]S}$ with equality holding when l = 0. This implies that for a given I_2, tying raises firm 1's investment (if $l > 0$); firm 1's reaction curve shifts outwards (see Figure 1). Tying strengthens firm 1's incentive to invest because firm 1 can no longer obtain a share l when the entrant is successful in a single component. Firm 1 can only benefit from its own innovation.

<< INSERT FIGURE 1 HERE >>

In contrast, when A1 and B1 are tied, firm 2's incentives for R&D investment are reduced if $p(R_2(I_1)) < 1/2$, where $p(R_2(I_1))$ is the best response success probability of the entrant under no tying (for a given I_1). This result is consistent with the earlier result in section 3 that the own effect dominates the cross effect if $p(I_2^*) < 1/2$. In particular, to compare the entrant's R&D incentives under tying and no tying, we observe that $\dfrac{1}{2[1-p(I_1)][1-l+2lp(I_2)]S} < \dfrac{1}{4[1-p(I_1)]p(I_2)S}$ if $p(I_2) < 1/2$. This implies that for a given I_1, tying induces firm 2 to invest less when $p(R_2(I_1)) < 1/2$. In this case, firm 2's reaction curve shifts to the left (see Figure 1). When, on the other hand, $p(R_2(I_1)) > 1/2$, tying causes firm 2's reaction curve to shift to the right (see Figure 1). Taken together with the stability of the Nash equilibrium, this implies that when $p(I_2^*) < 1/2$, we have $\tilde{I}_1^* > I_1^*$ and $\tilde{I}_2^* < I_2^*$.

Tying decisions

By causing strategic incentive distortions in stage 2, tying alters the equilibrium investment expenditures by firms 1 and 2. Firm 1 will choose to tie its components when tying increases its profits, i.e., when $D(l) = \tilde{\Pi}_1^* - \Pi_1^*(l) > 0$. Once again, we can demonstrate that firm 1 will practice tying at least for a range of l close to zero if $p(I_2^*) < 1/2$.

Specifically, consider the case where $l = 0$ with $p(I_2^*) < 1/2$. Notice that tying does not change firm 1's maximization problem when $l = 0$, while it causes the reaction curve of firm 2 to shift to the left (see Figure 2). Along the reaction curve of firm 1, the expected profits of firm 1 increase as firm 2 invests less.[25] As it is evident in Figure 2, tying increases the profits of firm 1; the new equilibrium point E' implies higher profits for firm 1. It follows that the inequality $\tilde{\Pi}_1^* > \Pi_1^*(l)$ is satisfied for a range of l greater than 0 because it holds strictly at $l = 0$.

<< INSERT FIGURE 2 HERE >>

Proposition 7: In the technological competition game, if $p(I_2^*) < 1/2$ when $l = 0$, then $\exists\, l' \in (0, 1)$ such that firm 1 ties A1 and B1 in stage 1 $\forall\, l \in [0, l')$.

As in section 3, tying reduces firm 2's incentive for investment when $p(I_2^*) < 1/2$ because the own effect dominates the cross effect. However, in this game, aside from protecting the incumbent's monopoly position, tying may also improve the incumbent's standing in technological competition.

Welfare effects

The overall effects of tying on total economic welfare are ambiguous in the technological competition model. A social planner seeking to maximize total economic welfare would have to maximize $2[p(I_1) + p(I_2) - p(I_1)p(I_2)]S - I_1 - I_2$ with respect to I_1 and I_2. The welfare maximization conditions would, thus, be

$$p'(I_1) = \frac{1}{2[1-p(I_2)]S}, \tag{31a}$$

$$p'(I_2) = \frac{1}{2[1-p(I_1)]S}. \tag{31b}$$

Since $\frac{1}{2[1-p(I_2)]S} > \frac{1}{2[1-p(I_2)][1+(1-l)p(I_2)]S}$, firm 1 overinvests in the no tying case compared with the social optimum (for each given level of I_2). Firm 1 overinvests because it can benefit from innovation in a component even if firm 2 has also succeeded. Firm 1 can take advantage of its monopoly position in the complementary component to engage in a price squeeze and extract the entire value of innovation when both firms succeed in the same component. Tying causes firm 1 to overinvest even more.

Firm 2, in contrast, underinvests in the no tying case compared with the social optimum (for each given level of I_1) when $p(R_2(I_1)) < 1/2$. Specifically, notice that $\frac{1}{2[1-p(I_1)]S} > \frac{1}{2[1-p(I_1)][1-l+2lp(I_2)]S}$ if $p(I_2) < 1/2$. Firm 2 faces two opposing effects. First, its investment incentives are weaker compared with the social optimum because it cannot capture the entire value of its success when it is the sole innovator in a single component. Firm 2 only obtains a share $1 - l$ of the cost savings S. On the other hand, its investment incentives are stronger because success in A2 will also benefit its other component B2 and vice versa, allowing firm 2 to capture the full value of innovation if it is successful in both components. If $p(R_2(I_1)) < 1/2$, the first effect dominates the second. Then, tying causes firm 2 to underinvest even more.[26]

By distorting strategic incentives in the investment stage, tying leads to different equilibrium investment levels of I_1 and I_2 (a higher I_1 and a lower I_2 if $p(I_2^*) < 1/2$). However, since we compare second best solutions, the effects of tying on total economic welfare are uncertain. Specifically, on a general level, there are two aspects of R&D to consider in evaluating the efficiency of R&D competition. First, R&D competition promotes a *diversity* of research lines and, thus, increases the aggregate probability of success if the outcome of the research project is uncertain. On the other hand, R&D competition can also lead to *duplication* of research efforts to the extent that their outcomes are correlated (Dasgupta and Maskin, 1987). If the probability of success is low, it is more likely that the positive effect of diversification outweighs the negative effect of duplication. In this case, tying will tend to reduce the efficiency of R&D competition. The reason is that when $p(I_2^*) < 1/2$, tying causes more research to be concentrated on the incumbent, reducing diversification. An additional negative effect of tying is that when innovation by only one entrant takes place, it cannot reach the market; tying blocks the sales of the low-cost technology.

The effects of tying on consumer welfare are also ambiguous in the technological competition model. There are four possible outcomes. When firm 2 does not succeed in both components, consumer surplus is zero. When firm 2 succeeds in both components and firm 1 in neither component, on the other hand, consumer surplus is $n(V - 2\bar{c})$. When firm 2 succeeds in both components and firm 1 in one component, consumer surplus is $n(V - \bar{c} - \underline{c})$. Finally, when both firms succeed in both components, consumer surplus is $n(V - 2\underline{c})$. Since we compare second-best solutions, the overall effects of tying on the probabilities of these outcomes, and, thus, on consumer welfare are uncertain. Nonetheless, it is likely that consumers will suffer from tying in this particular model since consumers benefit only when the entrant succeeds in both components, the probability of which is reduced with tying.[27]

5. Conclusion

The idea that an incumbent supplier may tie two complementary components to buttress its monopoly position is popular among practitioners yet has received little attention in formal economic theory. This paper has developed a simple formal model to identify when tying can be used as a defense against potential entry. To arrive at the dynamic version of the leverage theory, three basic assumptions were made: the initial presence of market power in all components, the existence of potential competition in all components, and the presence of a risky up-front investment. It has been shown that tying may make the prospects of entry less certain, discouraging the incumbent's rivals from investing and innovating. In these circumstances, tying may lead to lower consumer and total economic welfare.

Does the paper imply that tying is always an anticompetitive practice? Certainly not. For one thing, our reasoning depends on the probabilistic nature of investment; the argument is applicable only when the prospects of investment are uncertain. Also, in practice, the threat of entry in one of the components may be non-existent, so that tying may not be necessary to defend the incumbent's position.

Determining, then, the effects of tying is an empirical matter. It may be that the dynamic leverage theory is indeed relevant to some cases, while, in others tying is efficient, as the Chicago School contends. In any case, expressing the leverage doctrine in formal models can lead to a better appraisal of its strengths and weaknesses. The debate about tying cannot be conclusive unless formal models incorporate the aspects of the world that practitioners consider important.

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Footnotes

[1] If we extend the analysis, however, to allow for a *sequence* of potential entrants, the tying decision can also be optimal ex post. The reason is that allowing an entrant in one component market can facilitate future entry into the other component market, leading to an eventual displacement of the incumbent. See Choi and Stefanadis (2000) for a detailed analysis.

[2] United States v. Microsoft, Civil Case No. 98-1232 (1998).

[3] Microsoft's Windows operating systems are currently used on over 80 percent of Intel-based PCs, the dominant type of PC in the United States (U.S. Dept. of Justice, 1998). Also, the Internet Explorer's market share was 78 percent in November 1999 (Hamilton, 1999).

[4] Java still needs substantial refinement to become competitive; significant investments in product development are necessary before Java software can challenge Windows (Bank, 1999). Furthermore, the Internet browser market is highly dynamic and companies constantly have to make risky investments in new products. In these circumstances, tying may make the prospects of investment in the Netscape Navigator, or Java even more uncertain.

[5] Porter (1996), p. 73.

[6] United States v. Terminal Railroad Association of St. Lewis, 224 U.S. 383 (1912); International Business Machines v. United States, 298 U.S. 131 (1936); Standard Oil v. United States, 337 U.S. 293 (1949); Civil Aeronautics Board, Hearings for Proposed Rulemaking – Airline Computer Reservation Systems, EDR – 466 (1983).

The leverage doctrine was first discussed in the United States in the Terminal Railroad case. A group of railroads had formed a joint venture owning all the railroad bridges in St. Louis, and the antitrust authorities were concerned that the owners would exclude non-member competitors. The Supreme Court decided that tying access to the bridge to railroad service was a violation of the Sherman Act, and ruled that the owners had to provide access to competing railroads on reasonable terms.

[7] As Posner (1976), p. 173, notes, "a [fatal] weakness of the leverage theory is its inability to explain why a firm with a monopoly of one product would want to monopolize complementary products as well … To illustrate, let a purchaser of data processing be willing to pay up to $1 per unit of computation, requiring the use of one second of machine time and 10 punch cards, each of which costs 1c to produce. The computer monopolist can rent the computer for 90c a second and allow the user to buy cards on the open market for 1c, or, if tying is permitted, he can require the user to buy cards from him at 10c a card – but in that case he must reduce his machine rental charge to nothing, so what has he gained?"

[8] Bork (1978), p. 372.

[9] In Carbajo, De Meza, and Seidman (1990) and Chen (1997), on the other hand, tying is used as a device to segment the market and relax price competition.

[10] Furthermore, several articles in the literature examine the price discrimination argument of tying. See, for example, Adam and Yellen (1976), Schmalensee (1982), McAfee, McMillan, and Whinston (1989), and Mathewson and Winter (1997).

[11] This assumption enables us to bring out clearly the inefficiencies of tying. We will show that even if entrants have superior technology, the incumbent can block their entry.

[12] Our conclusions would be similar if the entrant's technological superiority were in the form of higher quality, rather than lower cost. Consider, for example, a game in which if an entrant succeeds in its investment, it has a product with value $V + (\bar{c} - \underline{c})$. If the entrant fails, on the other hand, the value of its

product is zero. The marginal cost of the entrant's product is always equal to $\bar{c}$. The outcome of this game would be exactly the same as in our basic model.

[13] Let Π_{A2} and Π_{B2} be the expected profits of A2 and B2 in the investment race. Π_{A2} and Π_{B2} will be derived in detail in the section on Investment decisions/No tying (for the no tying case) and the section on Investment decisions/Tying (denoted by $\tilde{\Pi}_{A2}$ and $\tilde{\Pi}_{B2}$ for the tying case). Global stability and uniqueness of equilibrium in the investment stage is ensured when $\partial^2\Pi_{A2}/\partial I_{A2}^2\partial^2\Pi_{B2}/\partial I_{B2}^2 - \partial^2\Pi_{A2}/\partial I_{A2}\partial I_{B2}\partial^2\Pi_{B2}/\partial I_{B2}\partial I_{A2} > 0$. Condition (1) leads to global stability and uniqueness both in the presence and in the absence of tying.

[14] For example, precommitment to tying is plausible in the context of the ongoing Microsoft case (*supra* note 1) if we believe Microsoft's claim that its operating system and its Web browser are so integrated that the browser, Internet Explorer, cannot be removed without disabling the operating system, Windows. The reason is that when Microsoft upgraded Internet Explorer to version 3.0, it placed some of the program's improved code into files that also contained instructions for operating system functions. The existence of common files, called dynamic linked libraries, in the design of software makes these two programs difficult to separate without jeopardizing the stability of each program. For instance, in a recent court filing, Microsoft argued that in the newly released Windows 98 operating system, Internet Explorer is so tightly integrated that it would "take many months (if not years) to develop and test" the operating system without the browser. Until then, the product "would be of no commercial value" (Lohr, 1998).

[15] This tie-breaking convention is standard in the analysis of Bertrand competition with *asymmetric* costs. It is equivalent to defining price equilibrium as the limit in which prices must be named in some discrete unit of account of size ε as $\varepsilon \to 0$.

[16] We thank an anonymous referee for suggesting to us to analyze the dependence of the monopolist's tying decision on the degree of price squeeze that is exercised by the incumbent.

[17] Let $I_{A2}^* = I'$ and $I_{B2}^* = I''$ be the equilibrium investment expenditures of A2 and B2 respectively, with $I' \neq I''$. Then, given the symmetry of the model, we would have another equilibrium in which $I_{A2}^* = I''$ and $I_{B2}^* = I'$; conditions (3) and (4) would still be satisfied. However, since the condition for global stability is met, we can only have a unique equilibrium in the investment race. It, thus, follows that in equilibrium $I' = I'' = I^*$.

[18] The condition for global stability (1) implies that the absolute value of $p''(I)p(I)$ is higher than $(p'(I))^2$. Furthermore, the concavity condition of $p(I)$ implies that $p''(I)p(I) < 0$. Thus, $p''(I)p(I) + (p'(I))^2 < 0$.

[19] Variables corresponding to tying are denoted by a tilde.

[20] Similar to note 17.

[21] If $\Pi_1^*(l)$ is a monotonically increasing function, there is a unique l such that $D(l) = 0$. However, the monotonicity of $\Pi_1^*(l)$ depends, inter alia, on the form of the probability function $p(I)$ and cannot be proved in general due to the existence of the indirect effects of l on the investment levels of entrants.

[22] When $l = 0$, the social planner's maximization problem would be identical to that of potential entrants in the case of no tying. By reducing A2's and B2's incentives for R&D investment, tying would still lower total economic welfare.

[23] Let $\Pi_2(I_{A2}, I_{B2})$ be the expected profit function of firm 2 in stage 2. Π_2 is concave when $\partial^2\Pi_2/\partial I_{A2}^2 < 0$ and $\partial^2\Pi_2/\partial I_{A2}^2\partial^2\Pi_2/\partial I_{B2}^2 - \partial^2\Pi_2/\partial I_{A2}\partial I_{B2}\,\partial^2\Pi_2/\partial I_{B2}\partial I_{A2} > 0$. Condition (1) ensures global concavity in both the tying and the no tying case.

[24] In particular, $\partial\Pi_1/\partial I_1\partial I_2 = -2p'(I_1)p'(I_2)lS < 0$, $\partial\Pi_2/\partial I_2\partial I_1 = -2p'(I_1)p'(I_2)[1 - l + 2lp(I_2)]S < 0$, $\partial\tilde{\Pi}_1/\partial I_1\partial I_2 = -4p'(I_1)\mathrm{p}'(I_2)\mathrm{p}(I_2)S < 0$, $\partial\tilde{\Pi}_2/\partial I_2\partial I_1 = -4p'(I_1)p'(I_2)p(I_2)S < 0$.

[25] In stage 2, along the reaction curve of firm 1, firm 1's profit, i.e. $n(V - 2\bar{c})[1 - p(I_2)^2] + 2p(I_1)[1 + p(I_2)][1 - p(I_2)]S - I_1$, becomes higher when firm 2 invests less. This follows from the envelope theorem: $-2p(I_2)p'(I_2)n(V - 2\bar{c}) - 4p(I_1)\,p(I_2)p'(I_2)S < 0$.

[26] When $p(R_2(I_1)) > 1/2$, on the other hand, tying cause firm 2 to overinvest even more.

[27] However, if tying entails other benefits for consumers, such as seamless integration of two complementary products, these benefits should be taken into account in the analysis.