TYING, UPGRADES, AND SWITCHING COSTS
IN DURABLE-GOODS MARKETS

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ABSTRACT

This paper investigates the role of product upgrades and consumer switching costs in the tying of

complementary products. Previous analyses of tying have found that a monopolist of one product

cannot increase its profits and reduce social welfare by tying and monopolizing a complementary

product if the initial monopolized product is essential, where essential means that all uses of the

complementary good require the initial monopolized product. We show that this is not true in

durable-goods settings characterized by product upgrades, where we show tying is especially

important when consumer switching costs are present. In addition to our results concerning tying our

analysis also provides a new rationale for leasing in durable-goods markets. We also discuss various

extensions including the role of the reversibility of tying as well as the antitrust implications of our

analysis.

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I. INTRODUCTION

Despite the increased interest in tie-in sales stimulated in part by the Microsoft case, little research has examined the consequences of tying a durable good to the purchase of a monopolized good. This is quite odd because many tie-ins such as Microsoft's tie-in of applications software with its operating system involve durable goods. This paper shows that certain features of durable goods such as upgrades and switching costs create an incentive to tie in a much broader set of circumstances than is suggested by the previous literature. Whinston's (1990) classic paper on tying derived conditions under which tying was not profitable. This paper shows that in durable-goods settings tying can be profitable even when those conditions appear to be satisfied. Moreover, this paper provides an explanation for some of Microsoft's behavior that previous theory has been unable to explain. Finally, this paper provides a new rationale for leasing.[1]

There are a number of analyses in which a monopolist of a primary product employs tying of a complementary product to monopolize the tied market and earn additional profits in that market.[2] A common feature shared by these analyses, however, is that the primary product is not essential. That is, there are uses of the complementary good that do not require the primary product. In fact, Whinston (1990) showed under a wide variety of conditions that, if the primary product is essential for all uses of the complementary good, then tying cannot be used to increase monopoly profits.[3] From the standpoint of applying these previous analyses to Microsoft's actions, this feature of those analyses is problematic. For the type of applications program that Microsoft bundles with Windows the Windows operating system is frequently essential, and thus these previous analyses provide little rationale for why Microsoft has chosen to bundle applications programs with Windows.

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[1] The only paper we are familiar with that looks at tying or similar behavior used to enhance market power in durable-goods markets is Morita and Waldman (2003). That paper, however, focuses on behavior analogous to a monopolist of a durable good tying a nondurable to the sale of the durable. In contrast, our focus is on what happens when the tied good is also durable. See Waldman (2003) for a general discussion of the durable-goods literature.

[2] A tie-in sale occurs when the seller of product A refuses to sell A to a consumer unless the consumer also purchases B. Product A is referred to as the tying product and B as the tied product.

[3] A number of previous authors argued that a monopolist of a primary product never has an incentive to tie in order to monopolize a complementary product (see Director and Levi (1956), Bowman (1957), Posner (1976), and Bork (1978)). Their argument was that the monopolist could capture all the potential monopoly profits through the primary-market monopoly. Whinston's analysis formalizes this argument but at the same time shows that it does not hold in all cases, i.e., where constant returns to scale and competition are lacking in the tied good and where the tying good is not essential (see also the earlier work of Ordover, Sykes, and Willig (1985)).

One approach to solving this puzzle is to shift attention away from the creation of market power in the tied good and instead focus on the return that tying might have in either preserving its monopoly in the tying market or extending its primary-market monopoly to newly-emerging markets.[4] We analyzed this possibility in Carlton and Waldman (2002) (see also Choi and Stefanidis (2001) and Nalebuff (2004)). There we considered a series of models that show how a monopolist can use tying to both preserve and extend monopoly positions in the tying good. For example, we considered models in which the alternative producer has a superior complementary product and in which the complementary market is characterized by either entry costs for the complementary good or network externalities. The alternative producer has an incentive to enter the primary good market because by doing so it can capture more of the surplus associated with its superior complementary product. What happens is that the monopolist ties and deters the alternative producer from entering the complementary market and this, in turn, reduces the incentive for subsequent entry into the primary market. Moreover, in variants of the model, we showed how the initial monopolist can transfer his monopoly power to new products as technology changes. We feel that these strategic uses of tying are some of the most important new lessons that economists can learn from studying Microsoft's behavior (and IBM's before it).

Our previous analysis formally shows how protecting its Windows monopoly can explain why Microsoft integrated Internet Explorer into Windows, but this reasoning is not a plausible explanation for all of Microsoft's tying decisions involving applications programs. That is, technological conditions in the browser case are such that a successful rival browser has the potential to evolve into a substitute for Windows so our explanation of tying used to protect the primary-market monopoly is quite plausible. But technological conditions consistent with our argument do not hold generally for applications programs, so protecting the primary-market monopoly is not a general explanation for Microsoft's tying decisions regarding applications programs.[5]

Given the inability of current theory to explain Microsoft's tying decisions regarding applications programs, we reexamine the question initially considered by Whinston which is, under what circumstances will a monopolist of a primary product tie a complementary product in order to extend its

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[4] Another possibility is that Microsoft is responding to efficiency considerations. See Evans and Salinger (2004) and Carlton and Perloff (2005) for discussions of efficiency rationales for tying.

[5] Gandal, Markovitch, and Riordan (2004) build on the classic analysis of Stigler (1963) concerning the negative correlation of values to provide an explanation for Microsoft's bundling strategy in the PC office software market. But their argument would seem not to apply to the bundling of Windows and applications programs.

monopoly to the tied market? We show that, if products are durable and product upgrades and consumer switching costs are characteristics of the complementary product (two characteristics clearly associated with many of Microsoft's applications programs), then a primary-good monopolist may indeed find it profitable to tie in order to monopolize a complementary market even when the primary product is essential for all uses of the complementary good.[6] Whinston's results on when tying is not profitable do not apply in our multi-period setting involving durable goods.

To understand the basic logic for our finding, we begin by reviewing the logic for Whinston's finding that a monopolist will not tie if the primary product is essential for all uses of the complementary good. Suppose the primary product is essential, the products are used in fixed proportions, marginal costs are constant, and consider a one-period setting. Further, suppose for a moment that the alternative producer cannot enter the complementary market. By setting the price for the complementary good at marginal cost and the price for the primary good at the optimal bundle price minus the complementary-good price, the monopolist can sell individual products and earn the same profits as it can by tying. Given this, suppose the alternative producer has the option of entering the complementary market but not the primary market and further suppose the monopolist does not tie. Since the monopolist can guarantee itself the profits associated with tying by setting the prices for the primary and complementary goods as before, if in equilibrium the alternative producer sells its complementary good this can only help monopoly profitability. Hence, the monopolist has no incentive to tie.

In this paper we develop two separate analyses that show the above argument breaks down in the presence of durable goods with the result that tying can be profitable even though the monopolist's primary good is essential for all uses of the complementary good. In our first analysis there are identical consumers who are in the market for two periods, upgrades for the complementary good but no switching costs, the alternative producer has a superior complementary product, and the monopolist's primary product is essential for all uses of the complementary good. Suppose further that the monopolist sells its products. Now the monopolist may tie in the first period not because this helps first-period profits (which cannot be the case given Whinston's results), but because of an increase in second-period profits when upgrades are sold. The logic here is that, because the alternative producer has a superior

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[6] There is an extensive literature that investigates models characterized by consumer switching costs. Papers in this literature include Klemperer (1987,1989) and Farrell and Shapiro (1988,1989). See Klemperer (1995) for a survey. There is also a literature concerning the upgrade process. See, for example, Fudenberg and Tirole (1998) and related analyses in Waldman (1996) and Lee and Lee (1998).

complementary product, in the absence of tying the alternative producer will typically sell complementary units in both periods while the monopolist will sell only the primary product in the first period. This means monopoly profitability in the second period equals zero, i.e., the monopolist has limited ability to capture potential profits associated with the upgrade process. As a result, if the benefit to upgrading is sufficiently high, then the monopolist will have an incentive to tie and stop the alternative producer from selling complementary units since the monopolist can then capture upgrade profits and in this way increase both second-period and overall profitability.

Our analysis reveals that an implicit assumption in Whinston's analysis that shows that tying is not profitable when the tying good is essential is that all the relevant sales take place simultaneously. This is a perfectly reasonable assumption for many nondurable products, but for durables it is not realistic. When all goods are sold simultaneously (and assuming the monopolist's primary good is essential), the monopolist need not tie to capture all the potential monopoly profits because appropriately choosing the prices for the individual products ensures the firm does at least as well as with tying. But this is not the case when some sales and thus some profits are realized in a later period. In our analysis, because upgrades are sold in the second period, the monopolist has limited ability to capture profits associated with upgrading by selling individual products and simply choosing the appropriate first-period prices for these individual products. Rather, if the firm sells its products and if second-period upgrade profits are large , the only way that the monopolist can capture all the profits associated with upgrading is by being the firm that sells the upgrades. In turn, when the alternative producer's complementary product is much superior to the monopolist's, the only way for the monopolist to sell upgrades in the second period is for the firm to sell a tied product in the first.[7]

Our first analysis also provides a new explanation for leasing in durable-goods markets.[8] That is, when we allow firms to lease as well as sell their products then we resurrect Whinston's results that tying

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[7] An assumption of our analysis is that the monopolist cannot charge negative prices for the complementary product. We discuss the exact role of this assumption in detail in Section IV. We also assume that the monopolist has limited ability to commit to future prices or write contracts with the alternative producer that bind future actions. Introducing such commitment ability would resurrect Whinston's result that tying is not needed when the primary product is essential. See the end of Section III for further discussion.

[8] There are a number of previous explanations for why durable-goods producers lease. Examples include the time-inconsistency argument of Coase (1972) and Bulow (1982), that leasing is used to remove lower quality used units from the market as in Waldman (1997) and Hendel and Lizzeri (1999), and that leasing is used to reduce problems due to adverse selection as shown in Hendel and Lizzeri (2002) and Johnson and Waldman (2003).

is unimportant as long as the tying good is essential. The reason is that in our first analysis the monopolist can capture second-period profits associated with upgrading by leasing and appropriately choosing second-period prices for its leased products.

In our second analysis we continue with the same basic framework of our first analysis but now we add consumer switching costs for the complementary good, i.e., in the second period a consumer places a positive value on consuming the same "brand" of the complementary good that he consumed in the first period. We show that introducing switching costs results in an even stronger motivation for the monopolist to tie in the sense that there are now parameterizations in which the monopolist ties not only in the case of selling but also in the case of leasing. The logic is that, if the alternative producer leases or sells complementary units in the first period, then the second-period benefits due to the switching costs are associated only with the alternative producer's complementary good. This means the monopolist cannot ensure that it will capture these benefits by marketing its products individually, leasing, and choosing appropriate prices. The result is that, if second-period upgrade and switching-cost profits are both high, then the monopolist ties in order to capture the extra second-period consumer benefits associated with an individual upgrading and consuming the same brand he consumed in the first period.

We also consider a number of extensions including the issue of reversible versus irreversible ties, i.e., when the monopolist ties does a consumer of the monopolist's product have the ability to use the alternative producer's complementary product (a reversible tie) or is this not feasible (an irreversible tie). We show that whether or not ties are reversible is critical for understanding whether or not tying will be used in the types of settings considered in our analysis. The returns to tying that we identify hold in the case of irreversible ties. When ties are reversible, in contrast, then tying is equivalent to setting the price of the complementary good to zero so there is no incremental return to the act of either contractually or physically tying the products. We relate this result to Microsoft's behavior in the design of Windows.

The outline for the paper is as follows. Section II considers a model characterized by upgrades but no switching costs and shows that tying can be optimal when firms sell as opposed to lease their products. Section III enriches the analysis in Section II by incorporating switching costs and shows that tying can be optimal in the case of selling or leasing. Section IV considers various extensions of our analysis including what happens when ties are reversible and when there are upgrades for both the primary and complementary goods. Section V discusses the antitrust implications of our analysis. Section VI presents some concluding remarks.

II. TYING IN THE PRESENCE OF COMPLEMENTARY-GOOD UPGRADES

In this section we analyze what happens when there are upgrades for the complementary product but no switching costs. Our focus will be on showing that, if the monopolist is restricted to selling its products, then the monopolist sometimes ties in order to capture potential profits associated with the upgrade process. However, we also show that tying is not useful if leasing is possible, thereby providing a new rationale for leasing. In the following section we consider how the results change when switching costs are added to the model.

A) <u>The Model</u>

We consider a two-period setting in which the monopolist is the sole producer in the primary market in both periods, say due to patenting, where the monopolist has a constant marginal cost for producing the primary good, denoted c_p. There is a complementary good that can be produced by the monopolist and a single other firm, where the monopolist and this alternative producer have the same constant marginal cost for producing the complementary good, denoted c_c. However, as described in more detail below, the alternative producer's complementary product is of higher quality than the monopolist's complementary product. Both primary and complementary products are durable so a unit purchased in the first period can be used in both periods, and the firms engage in Bertrand competition when more than one firm is active.

At the beginning of the second period each firm has the option of investing R and then selling higher quality complementary units in the second period (we discuss the possibility of primary-good upgrades in Section IV). Each of the N identical consumers receives a positive benefit from consuming a system where a system consists of one primary unit and one complementary unit, while no benefit is received from consuming either a primary unit by itself or a complementary unit by itself.[9] To be precise, in the first period a consumer derives a gross benefit from a system in which the complementary good is produced by the monopolist equal to V_M, while his gross benefit from a system in which the complementary good is produced by the alternative producer is V_A, where $V_A > V_M$ captures that the alternative producer's complementary product is higher quality. We also assume $2V_M > c_p + c_c$ to ensure

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[9] Because our models are characterized by identical consumers and each individual consumes either zero or one unit of each good in each period, the Coase time-inconsistency problem concerning durable-goods markets does not arise. See Coase (1972) and Bulow (1982) for analyses of this issue.

that production is profitable in this setting (note that this is the correct condition both because the primary and complementary products are durable and as indicated below there is no discounting).

If an individual consumes a system in the second period that contains the monopolist's complementary product, then he receives V_M if it is not an upgraded product and $V_M + \lambda$ if it is upgraded, where $N\lambda > R + Nc_c$ ($N\lambda > R + Nc_c$ means that upgrading is efficient). On the other hand, if an individual consumes a system in the second period that contains the alternative producer's complementary product, then he receives V_A if it is not an upgraded product and $V_A + \lambda$ if it is. In this specification λ is the return to consuming an upgraded product.[10]

In the beginning of the first period the monopolist decides whether to offer a tied product consisting of one unit of its primary and complementary goods or whether to offer the products individually.[11] Following Whinston (1990), we begin by assuming ties are irreversible which simply means that if the two goods are tied, a consumer cannot undo the tie. That is, if a consumer purchases a tied good consisting of one unit of the monopolist's primary good and one unit of its complementary good, then the consumer cannot add a unit of the alternative producer's complementary good to the system. As a result, if the monopolist offers a tied product, then the alternative producer does not sell any complementary units. We investigate the significance of this assumption in Section IV.[12] Note, however, if the monopolist ties in the first period and upgrades its complementary good in the second period, then a consumer who purchased the monopolist's tied product in the first period can add the upgraded product to his system in the second period.

Finally, to complete the set-up of the model, we adopt the following assumptions. First, to keep the analysis easy to follow we assume no discounting by either firms or consumers. Second, if a consumer purchases a complementary unit in the first period and then purchases an upgraded

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[10] As indicated, we assume that the upgrade value is the same for each firm. This is not important for our findings, but rather simplifies the exposition.

[11] There is no reason for the monopolist in the first period to offer both tied and individual products in this model because consumers are identical rather than heterogeneous. See Adams and Yellen (1976) for an analysis in which consumers are heterogeneous and firms sometimes offer both tied and individual products to more effectively price discriminate.

[12] From a real-world perspective, when a firm commits to bundle its products the resulting system can either be incompatible with the alternative producer's product or compatible with the alternative producer's product. The former case is what we mean when we say that consumers cannot undo ties, while we refer to the latter case as consumers being able to undo ties.

complementary unit in the second period, the used complementary good has no scrap value and there is no secondhand market on which to sell the used good.[13] Third, following Fudenberg and Tirole (1998) we allow a firm selling upgrades in the second period to price discriminate. That is, the firm has the ability to charge one price to consumers who are upgrading a used unit of the producer's complementary product and a different price to those who did not previously consume a complementary unit produced by the firm.[14] Fourth, we restrict attention to Pure-Strategy Subgame-Perfect Nash equilibria.[15]

The timing of the decisions is as follows. The first period consists of three stages. First, the monopolist chooses whether to have tied or individual products. Second, the firms simultaneuously choose prices for their products and whether or not to sell or lease when leasing is an option, where we restrict all prices to be non-negative.[16] Third, consumers then simultaneously choose which products to purchase (or lease when products are offered for lease). The second period then consists of three stages. First, the firms simultaneously choose whether to invest R and upgrade their complementary products. Second, the firms simultaneously choose prices for their products. Third, consumers simultaneously choose which products to purchase (or lease when products are offered for lease).

B) <u>Selling Only</u>

In this subsection we analyze the model under the assumption that firms are restricted to selling rather than leasing their products. Our main result is that, if firms are restricted to selling their products, then the introduction of upgrades makes tying a valuable tool for the monopolist. In particular, the

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[13] Introducing a secondhand market would not change any of the results because of our assumption that all consumers are identical. Similarly, introducing a positive scrap value would not substantially change our results.

[14] The firm can enforce this type of pricing either if the firm knows who bought its complementary product in the first period, or by offering a lower price in the second period for the upgraded complementary good for those who offer a used unit of the firm's complementary product as a trade-in. Imposing this assumption means, for example, that a consumer in equilibrium never delays purchasing the alternative producer's complementary product to the second period in order to take advantage of a low second-period price for the upgraded product. Also, we do not allow pricing for the primary product to be contingent on the consumption of a rival's product.

[15] We also restrict the analysis to symmetric equilibria, i.e., equilibria in which each of the N identical consumers employs the same equilibrium strategy.

[16] We assume the monopolist either sells both products or leases both products, i.e., we do not allow the monopolist, for example, to sell the primary good and lease the complementary good. This is not important for our results but it simplifies the analysis. Also, without loss of generality, we assume that a firm's first-period decision concerning selling or leasing is also binding for the second period. This entails no loss of generality because in our model there is no real difference between selling and leasing in the second period.

monopolist chooses to tie when the incremental benefit associated with upgrading and the extra quality associated with the alternative producer's superior complementary product are both sufficiently high.

We begin with a benchmark analysis in which there are no upgrades, i.e., $\lambda=0$. Our argument in this benchmark case is closely related to Whinston's first analysis of tying and complementary goods. In that analysis Whinston considers a setting in which, as in our model, all uses of the complementary good require the primary good, and shows that the monopolist has no incentive to tie because the monopolist is actually helped when the alternative producer enters the complementary market. We show that the same result holds in our model in the absence of upgrades. Let π_m denotes monopoly profitability in equilibrium while π_m^* denotes monopoly profitability in the absence of an alternative producer. Then the following proposition is true.

Proposition 1: Suppose firms sell their products and $\lambda=0$. Then there are multiple equilibria, where in one equilibrium the monopolist ties while in the other equilibria it does not. In the equilibrium in which the monopolist ties $\pi_m=\pi_m^*$, while every equilibrium in which the monopolist sells individual products is such that $\pi_m \geq \pi_m^*$ (where some of these equilibria are such that $\pi_m > \pi_m^*$).

Proposition 1 tells us that, in the absence of upgrades, the monopolist cannot increase its profitability by tying. That is, although there is an equilibrium in which the monopolist ties, this is not because the monopolist increases its profits by tying. As the proposition states, monopoly profitability in every equilibrium in which the firm sells individual products is at least as high as what the firm receives when it ties. Rather, in the tying equilibrium the monopolist is indifferent between tying and not tying because in that equilibrium it anticipates that, if it were to sell individual products, then its profitability would be the same as with tying.

The logic for this finding is the same as Whinston's argument referred to above. Suppose for a moment that the alternative producer cannot sell complementary units. By setting the price for the complementary good at marginal cost and the price for the primary good at the optimal bundle price minus the complementary-good price, the monopolist can sell individual products and earn the same profits as it can by tying. Given this, suppose the alternative producer has the option of selling complementary units and the monopolist does not tie. Since the monopolist can guarantee itself the profits associated with tying by setting the prices for the primary and complementary goods as before, it

follows that if the alternative producer sells its complementary good this cannot hurt monopoly profitability. Hence, in this case the monopolist may hurt profitability and cannot help profitability by tying. Or a simpler way to put this is that, if $\lambda=0$, then all transactions occur in the first period. In turn, since all sales occur simultaneously, then Whinston's logic applies.

One final comment about this first proposition concerns the idea that tying can actually hurt the monopolist in this initial setting. If the monopolist does not tie, then there are multiple equilibria many of which are characterized by consumers in the first period purchasing the primary good from the monopolist and the complementary good from the alternative producer. What varies across these equilibria is how the surplus associated with the alternative producer's superior complementary product is shared between the monopolist and the alternative producer. Any sharing rule between all the surplus being received by the monopolist and all being received by the alternative producer is possible. In a tying equilibrium the monopolist anticipates that if it sold individual products then it would not receive as profits any of the alternative producer's surplus, so tying does not hurt (but also does not help) the monopolist. There are, however, equilibria in which the monopolist does not tie and receives some of this surplus. In these equilibria the monopolist does not tie because it anticipates that tying would hurt profitability.

We now consider what happens when upgrades are introduced, i.e., λ is sufficiently large that upgrading occurs in equilibrium. This case works quite differently from the benchmark case analyzed above. The reason is that, as opposed to what is true when upgrades are not possible, the monopolist can no longer sell individual products and guarantee itself profits at least as high as under tying. The logic here is that with upgrades some profits are realized in the second period rather than in the first and the monopolist sometimes cannot fully capture those profits unless it is the firm that sells upgrades in the second period.

We begin our analysis of this case by considering behavior in period 2 as a function of what happens in period 1. We partially characterize this behavior in Lemma 1.[17]

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[17] Below we focus on what happens when consumers in the first period purchase the monopolist's primary product and the alternative producer's complementary product. Another interesting case is what happens if in the first period consumers purchase the monopolist's primary and complementary products. Then, if both firms upgrade, consumers purchase the alternative producer's complementary product at a price $(V_A-V_M)+c_c$. On the other hand, if only the alternative producer upgrades, then consumers purchase the alternative producer's complementary product at a price $(V_A-V_M)+\lambda$, while if only the monopolist upgrades then second-period behavior depends on the relative magnitudes of λ, V_A-V_M, and c_c.

<u>Lemma 1</u>: Suppose that all consumers in the first period purchase the monopolist's primary good and the alternative producer's complementary good. Holding all other parameters fixed, there exists a value V_A^* such that if $V_A > V_A^*$, then i), ii), and iii) characterize what happens in period 2.

      i) Only the alternative producer invests R and upgrades its complementary product.

      ii) All consumers purchase the upgraded complementary product from the alternative producer at a price λ.

      iii) The alternative producer earns second-period profits equal to $N(\lambda - c_c) - R$ while the monopolist's second-period profits equal zero.

Lemma 1 tells us that, if the alternative producer's quality advantage in the complementary product is sufficiently large and the alternative producer sold complementary units in the first period, then only the alternative producer will upgrade and sell complementary units in the second period. The logic here is as follows. If both firms invest R and upgrade their products, because the alternative producer has a superior complementary product, the alternative producer will sell complementary units in the second period at a price equal to $\min\{\lambda, (V_A - V_M) + c_c\}$. Given our assumption that $N\lambda > R + Nc_c$, this means that if V_A is sufficiently high, then the alternative producer will invest R and sell upgraded complementary units in the second period whether or not it anticipates that the monopolist will upgrade. In turn, since the monopolist knows this, in equilibrium only the alternative producer will choose to invest R and upgrade which means the firm will sell its upgraded product at a price of λ in the second period.

The reason this result is important is that it indicates that the logic behind Proposition 1 does not hold when upgrading occurs. In the absence of upgrading, the monopolist could sell individual products and price in such a way that it guarantees itself profits at least as high as with tying. But this is not true when upgrades are possible. Suppose the monopolist sells individual products and the alternative producer sells complementary units in the first period. Then in the first period the monopolist receives some share of the value associated with the alternative producer's superior complementary product, but in the second period the monopolist earns zero while the alternative producer receives $N(\lambda - c_c) - R$. On the other hand, if the monopolist ties, then it gives up any potential sharing of the surplus associated with the alternative producer's superior complementary product but in the second period it earns $N(\lambda - c_c) - R$. Given this, if $N(\lambda - c_c) - R$ is sufficiently large, the conclusion is that the monopolist must earn higher

profits by tying than by selling individual products and allowing the alternative producer to sell complementary units in the first period. This logic is expressed formally in Proposition 2 in which W denotes social welfare in equilibrium while W^N denotes welfare if the monopolist is restricted not to tie.

Proposition 2: Suppose firms sell as opposed to lease their products. Holding all other parameters fixed, if $V_A > V_A^*$ and λ is sufficiently large, then there is a unique equilibrium characterized by i) through iv).[18]

     i) The monopolist sells a tied product to all consumers in the first period.

     ii) The monopolist invests R at the beginning of the second period and sells an upgraded complementary product to all consumers in the second period at a price of λ.

     iii) The alternative producer does not sell complementary units in either period and does not invest R in the second period.

     iv) $W < W^N$.

An interesting aspect of Proposition 2 is that, when λ is sufficiently large, tying is preferred by the monopolist to selling individual products and setting the price for the complementary good at zero. The problem with the latter strategy is that it does not stop the alternative producer from selling complementary units in the first period and thus, in turn, being the seller of upgrades in the second period. Both because the alternative producer has a superior complementary good and because it will sell second-period upgrades if its sells complementary units in the first period, in response to a price of zero charged by the monopolist for the complementary good the alternative producer may choose to price sufficiently low that it sells complementary units in the first period. Even if this results in first-period losses for the alternative producer, this can be profitable for the alternative producer because of the subsequent profits the firm earns in the second period when it sells upgrades. Hence, when a zero price for the complementary good by the monopolist does not stop the alternative producer from selling complementary units, the monopolist may find that it maximizes profits by tying (in Section IV we discuss how the analysis changes when we relax the assumption that prices need to be non-negative).[19]

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[18] Without assuming $V_A > V_A^*$ we are not assured of a unique equilibrium. If λ is large but $V_A < V_A^*$, then there is always an equilibrium characterized by i) through iv) but it need not be unique.

[19] One important assumption both here and in the next section is that research and development is costly, i.e., R>0. If R=0, then both here and in the next section there would be no reason for the monopolist to tie. The reason is that

Another interesting aspect of Proposition 2 is that, as captured in iv) of the proposition, the act of tying reduces welfare. The logic is straightforward. As described, when the monopolist ties the result is that all consumers purchase primary and complementary units from the monopolist in the first period and then upgraded complementary units from the monopolist in the second period. Suppose instead the monopolist was not able to tie because of government regulation. Then all consumers would purchase primary units from the monopolist in the first period, complementary units from the alternative producer in the first period, and upgraded complementary units from the alternative producer in the second period. From a social-welfare standpoint the only difference between the two cases is that in the tying case consumers purchase the monopolist's lower quality complementary units rather than the alternative producer's higher quality complementary units. Given this, the act of tying clearly reduces welfare.

C) <u>Selling and Leasing</u>

We now turn our attention to what happens when firms can lease as well as sell their products. This analysis provides a new rationale for leasing. The reason the model works differently when leasing is an option is because, even without tying, by leasing its primary and complementary goods the monopolist provides itself with second-period prices from which it can extract profits due to upgrading. We formally consider this case in Proposition 3.

<u>Proposition 3</u>: Suppose firms can lease as well as sell their products in the presence of upgrades. For every allowable parameterization there are two equilibria characterized by the monopolist tying (in one it sells its products and in the other it leases) and in each $\pi_M = \pi_M^*$. There are also other equilibria in which the monopolist markets its products individually and every such equilibrium satisfies $\pi_M \geq \pi_M^*$ (where some of these equilibria are such that $\pi_M > \pi_M^*$).

Proposition 3 tells us that when leasing is an option the monopolist no longer has an incentive to tie even in the presence of upgrades. The result here is similar to what was found in Proposition 1. That is, although there are equilibria in which the monopolist ties, this is not because monopoly profitability is higher with tying. Rather, as was true in the analysis of Proposition 1, monopoly profitability in any

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with R=0 the monopolist's second-period complementary product is automatically upgraded, so the alternative producer's second-period profit would only reflect the superiority of its product rather than the upgrade value.

equilibrium in which the monopolist does not tie is at least as high and sometimes higher than in the tying cases. To be more precise, whenever the monopolist ties the firm is indifferent between tying and an alternative strategy in which it markets its products individually and earns the same profits as in the tying cases.

The logic here is a two-period variant of the logic in Whinston's paper described earlier. Suppose that in the first period the monopolist leases its products individually, charges marginal cost for its complementary good, and sets the primary-good price equal to the optimal first-period price for a leased bundle consisting of its primary and complementary goods minus the complementary-good price. This first-period strategy ensures first-period profits at least as high as first-period profits associated with leasing and tying. Now suppose that in the second period the monopolist upgrades its complementary good and then employs the same pricing strategy, i.e., the upgraded complementary good is priced at marginal cost and the price of the primary good is set equal to the optimal second-period price for a leased bundle consisting of primary and complementary goods minus the price of the upgraded complementary good. This ensures second-period profits at least as high as second-period profits associated with leasing and tying. Since tying yields the same profits whether or not the firm sells or leases, we now have that whenever tying is observed the firm could have done at least equally well by marketing its products individually.

An interesting aspect of this result is that, in contrast to tying, by leasing here the monopolist is able to capture second-period upgrade profits and also possibly share in the surplus associated with the alternative producer's superior complementary product. To see this, consider a parameterization in which λ is sufficiently large that, consistent with Proposition 2, the monopolist would tie if it was restricted to selling its products. For such a parameterization, if leasing is possible, then there are equilibria in which the monopolist leases individual products rather than ties. In some of these equilibria monopoly profitability is the same as with tying which means that the monopolist does not share in the surplus associated with the alternative producer's superior complementary product. But there are other equilibria in which the monopolist leases, does not tie, and profitability is higher than under tying. In these equilibria the monopolist both captures the second-period profit associated with upgrading and a positive share of the surplus associated with the alternative producer's superior complementary good.

What does Proposition 3 imply about social welfare? Let W* be social welfare in the absence of the alternative producer. In each tying equilibrium W=W* since tying means that the alternative

producer is not able to sell or lease its complementary product. Further, in an equilibrium in which the monopolist markets its products individually and $\pi_M > \pi_M^*$, then $W > W^*$ (if $\pi_M = \pi_M^*$, then $W \geq W^*$). The logic here is that, in the absence of an alternative producer, the monopolist extracts all the surplus, or, equivalently, both consumers and the alternative producer receive zero surplus. So, when $\pi_M > \pi_M^*$, the monopolist is better off while consumers and the alternative producer are no worse off, so social welfare must be higher.

In summary, in this section we have shown that a primary-good monopolist sometimes has an incentive to tie in a world in which the monopolist sells its products and there are upgrades for the complementary good. The rationale is that, in the absence of tying, the monopolist has limited ability to capture the value consumers place on the upgrade. Hence, if the upgrade is sufficiently valuable, then the monopolist may tie in order to capture those upgrade profits. The analysis also provides a new reason for why such a firm might lease but not tie since leasing is an alternative way for the firm to capture upgrade profits, and, in fact, in some cases leasing without tying will be preferred because it allows the firm to both capture upgrade profits and some of the profits due to the alternative producer's superior complementary product.

III. TYING IN THE PRESENCE OF UPGRADES AND SWITCHING COSTS

In this section we investigate how the analysis changes when consumer switching costs are introduced. Our main finding is that tying can now be optimal even if the primary-good monopolist has the option of leasing as well as selling its products. The reason is that, if consumer switching costs are substantial and individuals consume the alternative producer's complementary product in the first period, then in the second period the monopolist's upgraded complementary good becomes a less attractive substitute for the alternative producer's upgraded product and this limits the monopolist's ability to capture second-period profits due to the switching costs through leasing.

A) <u>The Model</u>

We now add consumer switching costs to the model. To understand what this means in our model, suppose that each firm upgrades at the beginning of the second period. Then an individual who consumes a unit of the monopolist's complementary good in the first period will have a higher valuation for the monopolist's upgrade in the second period than will an individual who consumed the alternative

producer's complementary good in the first period (an analogous statement holds for a consumer of the alternative producer's complementary product in the first period). One interpretation for the switching cost here is that the complementary product is associated with learning-by-doing. For example, if a consumer initially learned word processing using Word 2002 rather than Word Perfect 11, then he will typically prefer Word 2003 over Word Perfect 12 because of the similar ways in which Word 2002 and Word 2003 operate.

To be precise, the gross benefits that consumers receive in the second period from various consumption combinations are different than in the model of the previous section. Consider first an individual who consumed a system containing the monopolist's complementary good in the first period. If the individual consumes a system in the second period that contains the monopolist's complementary product, then he receives $V_M+\Delta$ if it is not an upgraded product and $V_M+\Delta+\lambda$ if it is upgraded, where $\Delta>0$. On the other hand, if the individual consumes a system in the second period that contains the alternative producer's complementary product, then he receives V_A if it is not an upgraded product and $V_A+\lambda$ if it is. In this specification Δ captures the switching costs, i.e., the consumer receives an added benefit if he consumes the same brand of the complementary product in the second period as in the first, while as before λ is the return to consuming an upgraded product.

Now consider an individual who consumed a system containing the alternative producer's complementary good in the first period. This case is symmetric to the one above. If the individual consumes a system in the second period that contains the alternative producer's complementary product, then he receives $V_A+\Delta$ if it is not an upgraded product and $V_A+\Delta+\lambda$ if it is. On the other hand, if the individual consumes a system in the second period that contains the monopolist's complementary product, then he receives V_M if it is not an upgraded product and $V_M+\lambda$ if it is.[20]

The other change that we introduce concerns how prices are determined. In the model under consideration, when the monopolist does not tie Bertrand competition does not typically result in a unique set of prices.[21] For example, suppose both firms lease, all consumers in the first period lease the

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[20] As indicated, we assume that the switching cost value is the same for each firm. As is true for the similar assumption for the upgrade value (see footnote 10), this is not important for our findings but rather simplifies the exposition.

[21] In terms of second-period prices which is our focus in terms of avoiding the multiplicity of prices, the problem only arises when the monopolist leases its products. Note that this multiplicity problem was also present in the previous analysis but there resolving the problem was not necessary for showing the return to tying.

alternative producer's complementary product, and both firms upgrade their complementary product at the beginning of the second period. Given this, consider pricing in the second period. One equilibrium set of second-period prices is that the monopolist charges $V_M+\lambda-c_c$ for its primary product and the alternative producer charges $(V_A-V_M)+\Delta+c_c$ for its upgraded complementary product (here and in the following set of equilibrium prices, consumers lease the complementary good from the alternative producer as long as the monopolist charges more than c_c for its complementary product). In this equilibrium to the second-period pricing subgame, the alternative producer receives all of the surplus associated with consumers preferring its version of the upgraded complementary product. However, in another set of equilibrium second-period prices, the monopolist charges $V_A+\Delta+\lambda-c_c$ for its primary product and the alternative producer charges c_c for its upgraded complementary product. In this equilibrium to the second-period pricing subgame, the monopolist receives all of the surplus associated with consumers preferring the alternative producer's version of the complementary good. In fact, any division across the two sellers is consistent with equilibrium.

Following the approach we took in Carlton and Waldman (2002), we assume that when this indeterminacy problem arises in the second period the prices that emerge evenly divide across the two sellers the surplus associated with consumers preferring the alternative producer's version of the complementary good (one interpretation of our assumption that the surplus is divided equally between the firms is that prices are determined by the Nash bargaining solution - see Nash (1950)). The same qualitative results would follow from any division that gave the alternative producer a strictly positive proportion of the surplus. If, on the other hand, the monopolist received all of the surplus, then when it can lease there would be no incentive for the monopolist to tie because leasing by itself would allow the firm to capture all the value associated with the consumer switching costs.[22]

B) Analysis

If firms are restricted to selling their products, then the results here are similar to the results of the previous section. First, if the alternative producer's complementary product is sufficiently superior,

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[22] We now also restrict the analysis to parameterizations for which $N(\lambda-c_c)/2>R$. Given our assumption concerning how the second-period multiple equilibria problem concerning prices is resolved this restriction ensures that, if consumers in the first period lease the monopolist's primary good and the alternative producer's complementary good, the alternative producer upgrades in the second period when the switching cost is sufficiently high. This assumption serves to reduce the number of cases that need to be considered.

then in the absence of the monopolist tying the alternative producer sells a complementary product in the first period and an upgraded complementary product in the second period. Second, in this situation the alternative producer earns second-period profits that are a linearly increasing function of the quality improvement due to upgrading, i.e., λ. Third, because of the limited ability of the monopolist to capture these second-period profits through the first-period sale of the primary good, if λ is sufficiently large then the monopolist ties and directly captures these second-period profits. Fourth, because tying forecloses a superior complementary product, for these parameterizations the act of tying reduces social welfare.

We now turn our attention to what happens when firms can either sell or lease their products. We begin with a preliminary result concerning what happens in the second period when in the first period all consumers lease primary units from the monopolist and complementary units from the alternative producer. Note that in the analysis of second-period behavior there is a potential multiple equilibria problem concerning the R&D decision. Similar to our analysis in Lemma 1 concerning what happens in the second period when firms only sell their output, we restrict the analysis in Lemma 2 to parameterizations in which the alternative producer's complementary product is sufficiently superior in period 2 that this multiple equilibria problem does not arise.

Lemma 2: Suppose that all consumers in the first period lease the monopolist's primary good and the alternative producer's complementary good. Holding all other parameters fixed, if Δ is sufficiently large, then i) through iv) characterize what happens in the second period.

    i) Both firms invest R and upgrade.

    ii) All consumers lease a primary unit from the monopolist and an upgraded complementary unit from the alternative producer.

    iii) The price for the monopolist's primary unit is $V_M+\lambda-c_c+[(V_A-V_M+\Delta)/2]$, while the price for the alternative producer's complementary unit is $c_c+[(V_A-V_M+\Delta)/2]$.[23]

    iv) The monopolist's second-period profits equal $N[V_M+\lambda-c_c+[(V_A-V_M+\Delta)/2]]-R$, while the alternative producer's profits equal $N[(V_A-V_M+\Delta)/2]-R$.

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[23] The sum of the price of the monopolist's primary unit and the price of the alternative producer's upgraded complementary unit is $V_A+\lambda+\Delta$, i.e., the gross benefit received by an individual consuming a system consisting of the monopolist's primary good and the alternative producer's upgraded complementary good.

Lemma 2 gives us a number of results concerning what happens in the second period when firms offer to lease rather than sell their products and in the first period consumers lease primary units from the monopolist and complementary units from the alternative producer. First, if the switching cost is sufficiently large, then there is a unique equilibrium in which both firms upgrade and consumers lease primary units from the monopolist and upgraded complementary units from the alternative producer. Note that the return here for the monopolist to upgrade even though it does not sell upgraded complementary units in the second period is that upgrading allows the monopolist to raise the lease price for the primary product and in this way capture all of λ.[24] Second, abstracting from the upgrade cost, the monopolist captures all of the profits due to the improved upgrade quality. Third, even though the monopolist upgrades, its second-period profit is such that the monopolist captures only half of the second-period profit due to the switching cost while the other half is captured by the alternative producer.

It is the second and third results that we want to focus on. The second result is an example of the main point of Proposition 3 of the previous section. That is, when the monopolist leases in the first period, it always has the option in the second period of upgrading its complementary unit and in this way capturing the second-period profits due to the increased upgrade quality. As a result, as captured in Proposition 3 of the previous section, if there are upgrades but no switching costs and the monopolist has the option of leasing, then it never has an incentive to tie because it can use a leasing strategy to capture the profits due to upgrading and thus marketing its products individually does at least as well as tying.

The third result described above tells us that in terms of second-period behavior the model works quite differently for switching costs than it does for the quality improvement due to the complementary-good upgrade. As just described, the monopolist can capture all of the second-period profits due to the upgrade process by leasing and upgrading in the second period. In contrast, even when the monopolist upgrades, Lemma 2.iii) and 2.iv) tell us that if in the first period consumers lease the monopolist's primary good and the alternative producer's complementary good, then second-period prices are such that the monopolist only captures half of the second-period profits due to the switching costs. Note, however, that if the monopolist ties (whether or not it leases or sells its tied product), the monopolist captures all of the second-period profits due to the switching costs. The result is that, if the switching

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[24] If we interpret second-period prices as being determined by Nash bargaining, then by upgrading the monopolist improves its second-period threat point.

cost is sufficiently large, then the monopolist may have an incentive to tie. This logic is expressed formally in Proposition 4.

Proposition 4: Suppose firms can either sell or lease their products. Holding all other parameters fixed, if λ and Δ are both sufficiently large, then i) through v) characterize equilibrium behavior.

       i) The monopolist either sells or leases a tied product to all consumers in the first period.

       ii) The monopolist invests R at the beginning of the second period.

       iii) If the monopolist sold (leased) a tied product in the first period, then it sells an upgraded complementary good to all consumers in the second period (leases a tied good consisting of a primary unit and an upgraded complementary unit to all consumers in the second period).

       iv) The alternative producer does not sell or lease complementary units in either period and does not invest R in the second period.

       v) If $2N(V_A-V_M)>R$, then $W<W^N$.

In Whinston's (1990) classic analysis the monopolist never ties when its primary good is essential for all uses of the complementary good. Whinston considers a one-period setting and shows that the monopolist never ties when its primary product is essential because it can sell its products individually and set the prices for its products so that it is guaranteed at least the same profits as it earns by tying. Proposition 2 shows that this result is not robust to the introduction of durable goods, upgrades, and a selling-only policy, but Proposition 3 shows that it is if leasing is allowed. Proposition 4 shows that this result is not robust to the introduction of durable goods, upgrades, and switching costs even when the monopolist has the option of leasing.

      What underlied Proposition 3 is that, if we were to take as fixed the value in each period that consumers have for the various products, then by leasing individual products and upgrading, the monopolist can guarantee itself in each period the same profits as it earns by tying. But this logic does not eliminate the incentive to tie in the presence of consumer switching costs. The reason is that, if the monopolist leases, upgrades in the second period, and the alternative producer leases or sells complementary units in the first period, then because of the switching costs in the second period the monopolist's complementary product is perceived by the first-period consumers of the alternative producer's complementary good to be lower in value than if the monopolist had leased or sold a tied

product in the first period. The result is that the monopolist's second-period profit is not guaranteed to be as high as if it leased a tied unit in each period, and if the switching cost is sufficiently high this logic translates into an incentive for the monopolis to tie.

To be more precise, suppose the monopolist leases, does not tie, and upgrades in the second period. If consumers lease the alternative producer's complementary product in the first period and the alternative producer upgrades in the second period, our assumption that the surplus in the second period is split evenly across the firms means the monopolist's second-period profit equals $N(V_M+\lambda-c_c)-R +N((V_A-V_M+\Delta)/2)$. In contrast, by tying, leasing, and upgrading, the monopolist achieves second-period profit equal to $N(V_M+\lambda+\Delta-c_c)-R$. In other words, tying allows the monopolist to capture all the second-period value due to the switching costs but none of the value due to the alternative producer's superior complementary product, while not tying and having individuals in the first period consume the alternative producer's complementary product means that in the second period the monopolist captures half of the value due to both switching costs and the alternative producer's superior complementary product. If Δ is sufficiently large, the tying outcome is preferred.

One interesting aspect of Proposition 4 is that both λ and Δ have to be large to ensure that tying is employed. From the discussion in the above paragraph, one might think that only Δ needs to be large to ensure tying is employed. But the above paragraph assumes that, if the monopolist does not tie, its alternative strategy is to lease. But this is not necessarily the case. It is possible that the monopolist's best alternative strategy is to sell its products rather than lease. Further, one can show that, if the monopolist's best alternative is to sell rather than lease, then it is possible that it is able to capture much of the value of the second-period switching cost through the first-period sale of the primary product. But from Proposition 2 we know that, if the monopolist sells, then its profitability is lower than tying profitability if λ is sufficiently large. Hence, if λ and Δ are both sufficiently large, then the monopolist must maximize its profits by tying.

Another interesting aspect of Proposition 4 is that, in contrast to what was true in Proposition 2, tying used to monopolize the complementary market does not always hurt social welfare. If, in the absence of the ability to tie, the monopolist would sell its products, then as in Proposition 2 tying can only hurt social welfare. However, if the absence of tying means the monopolist leases, then tying can in fact improve social welfare. The logic here is as follows. For some parameterizations, if the monopolist is restricted not to tie, then it leases, both firms upgrade, and individuals in the second period consume

the monopolist's primary product and the alternative producer's complementary product (as noted before, the monopolist upgrades because this reduces the surplus associated with the alternative producer's complementary product which, in turn, increases the second-period price for the monopolist's primary good).[25] For these parameterizations, tying has two effects on social welfare. The first is that there is a social welfare cost equal to $2N(V_A-V_M)$ because individuals consume the monopolist's lower quality complementary product, but there is also a social-welfare benefit equal to R because only the monopolist invests. In these parameterizations, social welfare increases with tying if $2N(V_A-V_M)<R$. However, if $2N(V_A-V_M)>R$, then tying decreases social welfare in these parameterizations. So, if $2N(V_A-V_M)>R$, then, as captured in Proposition 4, tying necessarily decreases social welfare.

As a final point, a key assumption of our argument here and in the previous section is that the monopolist and alternative producer cannot write long-term contracts in the first period that bind themselves to specific actions in the second period. If they could do this in an unconstrained way, then the monopolist would not have an incentive to tie because there would always be a long-term contract consistent with individuals consuming the alternative producer's superior complementary product in which profits are shared in such a way that both firms are better off than if the monopolist tied. Further, in addition to making both firms better off, social welfare would also rise because individuals would consume the alternative producer's superior complementary product and only the alternative producer would invest in research and development. Despite the positive outcomes associated with such contracting, however, in real-world situations such contracts are frequently difficult or infeasible because of the difficulty of monitoring and enforcing contractual commitments concerning research and development and prices.

In summary, in this section we have shown that in the presence of consumer switching costs, even when the monopolist can lease, the monopolist can have an incentive to tie even though the monopolist's primary good is essential for all uses of the complementary good. The reason is that the switching cost means that if individuals consume the alternative producer's complementary product in the first period, then the monopolist's complementary product in the second period is perceived as lower

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[25] In our model, because all consumers are identical, no individuals consume the monopolist's upgraded complementary product in the second period. One could enrich the model, however, by adding some consumer heterogeneity, and have similar results where some individuals consume the monopolist's upgraded complementary units in the second period but the main goal of the monopolist in upgrading is to reduce for the bulk of consumers the surplus associated with the alternative producer's second-period complementary product.

quality and thus a worse substitute for the alternative producer's complementary product. In other words, with switching costs the only way the monopolist can capture all of Δ is to have individuals consume the monopolist's complementary product in the first period. The monopolist's ability to extract all of Δ in period 2 depends on individuals consuming the monopolist's complementary product in period 1. Only a tie will do this. We also showed that tying in this case will frequently decrease social welfare, but in contrast to the analysis in the previous section this is not always the case. It can decrease social welfare because it results in individuals consuming lower quality complementary units. But it can also increase social welfare because for some parameterizations it reduces the aggregate expenditure on R&D.

IV. EXTENSIONS

The previous two sections showed how the introduction of upgrades and switching costs can result in tying by a primary-good monopolist being optimal even when the monopolist's primary good is essential for all uses of the complementary product. In this section we discuss the robustness of our results to three ways of extending our analysis: i) the introduction of reversible ties; ii) relaxing the constraint on non-negative prices; and iii) the introduction of primary-product upgrades.

Extension 1: Reversible Ties

Following Whinston (1990), in the analyses of Sections II and III we assumed that ties were not reversible, i.e., when the monopolist tied its primary and complementary products it was impossible for consumers to reverse the tie and make use of the alternative producer's complementary product. At least for the case of Microsoft this assumption is not always correct in that consumers can typically add an alternative producer's complementary product to Windows even when Microsoft has tied a similar product to the Windows operating system. In this discussion we consider what happens when, starting from a situation for which one of our earlier analyses indicates tying, we relax this assumption.

Suppose we instead assume that ties are completely reversible, i.e., when the monopolist ties its products there is no added cost associated with consumers adding the alternative producer's complementary product to a system already consisting of the monopolist's primary and complementary products. In this case there would be no parameterizations in which tying is the unique equilibrium outcome. The reason is that under perfect reversibility tying is equivalent to having the monopolist set the price of the complementary good at zero. Hence, if there is an equilibrium in which the monopolist

ties in order to stop consumers from purchasing or leasing the alternative producer's complementary products, there must also be an equilibrium in which the monopolist markets its products individually but sets the price of the complementary good at zero.

Another possibility is that ties are somewhere between being perfectly reversible and perfectly irreversible. That is, when the monopolist ties it is still possible for a consumer to add the alternative producer's complementary product to a system consisting of the monopolist's primary and complementary goods, but there is an added cost of doing so. This added cost can be in the form of an added cost faced by the consumer, an increase in the alternative producer's cost structure , or a lowering of the functionality of the alternative producer's product. For any of these cases, there will be some parameterizations in which the monopolist ties in order to stop consumers from purchasing or leasing the alternative producer's complementary products.

The logic for this result is as follows. For some parameterizations in which the monopolist wants to prohibit the alternative producer from selling or leasing its complementary good, the monopolist can achieve this result by setting the price for its complementary good at zero. However, for other parameterizations a zero price for its complementary good is not low enough to foreclose the alternative producer from the complementary-good market, but a sufficiently low negative price would foreclose the alternative producer. For any such parameterization, if ties are reversible but cause an increase in the cost associated with consumers adding the alternative producer's product to a system, then the monopolist will tie if this cost is sufficiently large. The reason is that, in this case, tying is equivalent to setting a negative price for the complementary good equal to the added cost. In turn, since a sufficiently low negative price for the monopolist's complementary good makes it unprofitable for the alternative producer to sell or lease its product, the monopolist will tie if this cost is sufficiently large.[26]

What is interesting about this discussion is that it is consistent with many of Microsoft's tying decisions. In many cases it is not just that Microsoft packages Windows and the applications program together, but in addition Microsoft takes actions that arguably make it more costly for consumers to use alternative producers' products.[27] Specifically, Microsoft frequently integrates the applications program directly into the Windows programming code rather than having the applications program be distinct

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[26] The argument here is an example of the idea that firms sometimes have an incentive to behave in ways that raise rivals' costs. See Salop and Scheffman (1983,1987) for early analyses of this idea.

[27] See Gilbert and Katz (2001) and Whinston (2001) for discussions of Microsoft's behavior.

code that connects to Windows through an interface. This can make it more costly for consumers to use alternative producers' products.[28] Additionally, Microsoft tries to keep some applications programming interfaces secret which directly serves to either increase alternative producers' costs or lower the functionality of the alternative producers' products. The discussion in this section provides one explanation for how this behavior can be in Microsoft's interests.

Extension 2: Relaxing the Constraint on Non-Negative Prices

An important aspect of our argument is that the monopolist has limited ability to capture second-period consumer value associated with upgrades and consumer switching costs through first-period prices and first-period competition for the lease or sale of complementary units. Such competition is clearly limited in our model because we assume that prices – in particular, first-period prices for the complementary good – cannot be negative (or contingent on second-period actions). Here we discuss how the analysis would change given various ways of relaxing this constraint.

One way to relax the constraint is to allow negative prices, but retain the assumption that there is a lower bound on the price that can be charged for a complementary unit. In other words, instead of the lower bound on the complementary-good price being zero, assume it equals some value P_c^L, $P_c^L<0$. This change basically has no effect on the qualitative nature of the results. It would still be the case in Proposition 2 that i) through iv) would hold for λ sufficiently large, i.e., in the case in which firms are restricted to selling their products the monopolist would tie if the increase in quality associated with upgrading was sufficiently large. Also, in Proposition 4 it would still be the case that i) through v) would hold for λ and Δ sufficiently large, i.e, in the case in which firms can sell or lease the monopolist would tie given sufficiently large upgrade profits and sufficiently large switching costs. The only changes are that in the former case for any parameterization the minimum λ required for tying to be optimal would be higher, while in the latter case for any parameterization the minimum λ and Δ required for tying to be optimal would be higher.

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[28] When Microsoft integrates the applications program directly into Windows the result can be the same as keeping applications programming interfaces secret. That is, such integration makes it more difficult or maybe even impossible for an alternative producer to reverse engineer Microsoft's applications program and have the alternative producer's product interface with Windows in the same way that Microsoft's program does. The result is that alternative producers face higher costs or there is a reduction in the functionality of alternative producers' products.

A second way to relax the non-negative price constraint is to assume that firms are allowed to set any price no matter how negative, but that firms are not able to monitor and ration how many units a consumer leases or purchases. Relaxing the assumption this way has no effect on our results. The reason is that under this assumption, although strictly negative prices are part of the choice set, no firm would ever choose to charge a strictly negative price in equilibrium. This is because, if a firm were to charge a strictly negative price, consumers would maximize their net benefits by purchasing or leasing multiple units of the good with the strictly negative price (an infinite number of units if allowed) thus driving down the firm's profitability.[29]

A third way of relaxing the non-negative price constraint is to assume that both the monopolist and the alternative producer can charge strictly negative prices, each consumer can be limited to leasing or purchasing a single unit of a product, and the monopolist can price discriminate in the sense that only consumers who purchase or lease a primary unit in the first period would be offered a strictly negative first-period price for the complementary unit. If we assume that in addition to the N identical consumers that we assume in our basic analyses that there are a large number of consumers who place no value on the primary and complementary products (see footnote 29 for a related discussion), then even this assumption has no effect on the qualitative nature of the results. The reason is that, given the existence of the additional consumers, the monopolist would be constrained to have the sum of first-period primary- and complementary-good prices be non-negative. As a result, for sufficiently large λ the monopolist would still want to tie in Proposition 2 and for sufficiently large λ and Δ the monopolist would still want to tie in Proposition 4.

In other words, one can relax the non-negative price constraint in various ways without changing the qualitative nature of the results. One change that would affect the results is to assume that purchasing or leasing at a strictly negative price in the first period would obligate the consumer to purchase or lease the firm's upgraded complementary good at some strictly positive price in the second period. This would

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[29] An alternative way of relaxing the non-negative price constraint would be to assume that firms can limit each consumer to purchasing or leasing a single unit, but that in addition to the N identical consumers that we assume there are a large number of consumers who place no value on the primary and complementary goods. As described above for the case in which no monitoring and rationing is possible, this way of relaxing the non-negative price constraint would have no effect on the results. The reason is that, similar to the logic in the no-monitoring and rationing case, if a firm set a strictly negative price its profits would be driven down because it would attract consumers who purchased or leased at the strictly negative price and purchased or leased nothing else.

allow a firm to charge a strictly negative price in the first period without attracting consumers whose first-period purchasing and leasing contribute negatively to the firm's overall profit. But there are various reasons why this type of long-term contract might be difficult in practice. For example, one could incorporate a potential moral-hazard problem in which firms could either invest R or zero in the research and development of the upgraded complementary product. In such a world this type of long-term contract would be problematic because the firm requiring the commitment on the part of its consumers would lose the incentive to invest R and develop a high-quality upgrade.

Extension 3: Primary-Product Upgrades

In Sections II and III we assumed there were upgrades for the complementary good, but no upgrades for the monopolist's primary product. But clearly the real-world situations that our analysis is trying to address such as Microsoft's behavior concerning Windows and IBM's behavior in an earlier era were characterized by upgrades for both primary and complementary goods. In this section we discuss how our analysis changes when primary-good upgrades are introduced.

Consider first the analysis of Section II in which there are no complementary-good switching costs. We found that, if firms can sell or lease, then there is no reason for the monopolist to tie. In that case introducing the option for the monopolist to invest in R&D and introduce a primary-good upgrade in the second period does not change the basic conclusion, i.e., there is still no reason for the monopolist to tie. The reason is that the monopolist can still ensure itself profits at least equal to tying by selling individual products, upgrading, and pricing the complementary good each period at marginal cost.

Now suppose that firms can only sell their products. At first one might think this should eliminate the result that tying can be optimal because the monopolist can capture the second-period complementary-good upgrade profits by optimally setting the second-period prices for its primary and complementary goods. But this is incorrect. Because in the second period consumers own the monopolist's old primary good, consumers have the option of purchasing the alternative producer's upgraded complementary good and nothing else. As a result, the monopolist has limited ability to capture second-period complementary-good-upgrade profits by appropriately pricing individual products which means that for some parameterizations tying will still be optimal.

Now consider the analysis of Section III in which there are complementary-good switching costs. In this case we found that, if the switching costs and upgrade valuations are both sufficiently large, then

the monopolist has an incentive to tie even when leasing is possible. The reason is that, if the monopolist leases and individuals consume the alternative producer's complementary good in the first period, then in the second period the monopolist's complementary good is less attractive which means optimal pricing of second-period goods gives the monopolist limited ability to capture second-period profits that are due to the switching costs. Now suppose in that analysis we introduced the option for the monopolist to invest in R&D and introduce a primary-good upgrade in the second period. Even with an upgraded primary product, the monopolist would have limited ability to capture second-period switching cost profits by leasing individual products and optimally pricing second-period goods. Hence, the basic finding that the monopolist would have an incentive to tie when switching costs are sufficiently large would be unchanged. Or, in summary, from a qualitative standpoint, none of our results are affected by the introduction of primary-product upgrades.

V. ANTITRUST IMPLICATIONS

A model such as ours showing that tie-in sales can be used to harm social welfare under certain circumstances would seem to suggest a basis for more vigorous antitrust enforcement. But such reasoning is dangerous for several reasons.[30] First, tie-in sales generally are designed to promote efficiencies. Indeed, every product can be thought of as a tie-in sale, so any attack on the practice is likely to cause some harm to the extent it makes firms reluctant to use the practice. Second, the only way to prevent a physical tie (as opposed to a contractual tie) is to interfere with the product design decision. This is akin to intervening within the firm. Such intervention is rare in antitrust enforcement and for good reason, since the increased transaction cost of forcing transactions outside the firm could be large, as well as hard to determine ex ante.

Intervention when contracts, rather than product design, are used to effectuate the tie would be consistent with current antitrust treatment. For example, exclusive distribution achieved through contract has been attacked recently under our antitrust laws but exclusive distribution by the firm itself has not. Even here, we would urge caution since our models show that tie-ins can have ambiguous welfare consequences, and we are not convinced that economists can reliably identify ex ante those situations where welfare will decrease. Our concern is heightened by the fact that relatively modest changes in

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[30] See Carlton and Waldman (2005) for a related discussion.

assumptions can alter some of the model's results. For example, as stressed in our exposition, it is the non-simultaneity of transactions together with the dynamic pattern of play that yields our results. Although we believe our sequencing of decisions is reasonable for many industries, a change in that sequencing could alter our results. We fear the enthusiasm to bring an antitrust case will obscure the difficulty of reliably identifying the sequencing decision. In those situations where the facts indicate that our model applies, we recommend great caution before condemning a practice, giving great weight to plausible efficiencies.

There are however two clear implications for antitrust policy from our results. First, whenever a superior complementary producer exists and the monopolist ties in order to exclude this alternative producer, there is an incentive for a transaction to occur that eliminates the inefficiency of not using the superior product. In such a case a merger between the monopolist and the producer of the superior complementary good would be desirable, even though it appears to turn a possible duopoly in the complementary good into a monopoly. Second, absent a merger, there is an incentive for the producer of the superior complementary good to sign a contract with the monopolist to effectuate a tie that results in consumption of the efficient product. One problem with this contract is dynamic consistency of incentives since investments in the second period need to be made. This contract could restore efficiency but would require significant monitoring to overcome any dynamic inconsistencies. Such detailed contracts are likely to raise the same antitrust question as a merger, yet like a merger could be efficient.[31]

VI. CONCLUSION

The literature has identified various reasons for why a firm selling complementary products might tie including efficiency rationales, enhanced price discrimination, and monopolizing the tied-good market. But the literature also indicates that in an important class of cases, i.e., settings in which the products are complementary and the tying good is essential, a monopolist of a primary good would never tie in order to earn monopoly profits in the tied-good market. Since arguably many important real-world tying cases fall in this category including some of Microsoft's tying decisions and also IBM's in an earlier era, the literature's result concerning whether one of the products is essential has important policy

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[31] We note that incentives to behave efficiently create incentives to alter the game played and the sequencing of decisions. Making the game and decisions sequence endogenous would clearly be the right research path to pursue, but it is one that to our knowledge has had few, if any, contributions.

implications about the desirability of tying. The focus of this paper has been to show that the result that a monopolist of an essential primary good will never tie in order to earn monopoly profits in the tied-good market does not apply when goods are durable.

The idea that a monopolist of a primary good would never tie in order to monopolize a complementary-good market when the primary product is essential was originally shown in Whinston (1990) in a one-period model. Our analysis shows that two features of durable goods, product upgrades and consumer switching costs (both of which are prominent features of the Microsoft setting), can undo Whinston's result in two ways. The first is that, if firms only sell their products, then tying in the first period can help the monopolist capture profits associated with upgrade sales in the second period. This occurs because, if the monopolist sells individual products and it is the alternative producer who sells complementary units, then there are no second-period sales from which the monopolist can capture second-period profits due to the upgrade. This analysis also implies a rationale for leasing as an alternative to selling and tying. The second is that, even if firms can lease, as long as switching costs are also important, then tying may be used in order to capture the second-period profits associated with the switching cost. The logic here is that, if the monopolist leases individual products and in the first period individuals consume the alternative producer's complementary product, then the monopolist has limited ability to capture second-period profits due to the switching cost because the switching cost increases the second-period difference in the value consumers place on the two complementary products.

In terms of the continuing public policy debate about Microsoft's behavior, this paper and our earlier tying paper show that there are various theoretical arguments consistent with many of Microsoft's tying decisions being driven by a desire to monopolize. In our earlier paper, we showed that some of these decisions may be driven by a desire by Microsoft to preserve and extend its Windows monopoly. In this paper, we show that some of these decisions may be driven by a desire by Microsoft to monopolize markets that are complementary to Windows. Although theoretical possibility by itself does not prove what Microsoft's true motivations are, we believe that our two papers together throw doubt on the contention by some that economic theory does not support monopolization arguments in the type of environment inhabited by Microsoft today and IBM in an earlier era. Despite this, we remain wary of overzealous use of antitrust to attack tie-in sales.

There are a number of directions in which the analysis in this paper can be extended, but three stand out. First, we have considered two-period models with a single cohort of consumers who are in the

market in both periods. It might be of interest to extend the model so that there is a flow of new consumers in each period, in order to see how consumer growth affects the results. Second, in our analysis the qualities of the initial products and the qualities associated with upgrading are taken as fixed as opposed to being decision variables of the primary-good monopolist and the alternative producer of the complementary good. Given the interest in how Microsoft's tying behavior affects the pace of innovation in the software industry, an interesting extension would be to incorporate into our analysis R&D choices that endogenously determine initial and upgrade qualities.[32] Third, it might be fruitful to investigate how product-design decisions can influence the timing of moves and, in turn, equilibrium outcomes of our multi-period game.

APPENDIX

Proof of Proposition 1: Suppose first that the monopolist ties. Then the alternative producer is not able to sell its complementary product. Because consumers are identical and $\lambda=0$, in this case equilibrium behavior is that the monopolist charges $2V_M$ for the tied product in the first period, neither firm invests, and consumers purchase the tied product in the first period. This yields monopoly profits the same as if there were no alternative producer, i.e., $\pi_M=\pi_M^*=N[2V_M-c_p-c_c]$.

Now suppose the monopolist does not tie. One equilibrium to the resulting subgame is that the monopolist charges V_M-c_c for the primary product, $c_c+\varepsilon$ for its complementary product, the alternative producer charges $(V_A-V_M)+c_c$ for its complementary product, and consumers in the first period purchase primary units from the monopolist and complementary units from the alternative producer (this is equilibrium behavior since each firm's pricing strategy is a best response to the other firm's pricing strategy). This yields the monopolist $\pi_M=\pi_M^*$. Notice that since it is possible that the monopolist anticipates that this will be the equilibrium if the monopolist does not tie, one equilibrium to the full game is that the monopolist ties and $\pi_M=\pi_M^*$.

Suppose again the monopolist does not tie. Since the monopolist had the option of tying and earning π_M^*, any equilibrium in which the monopolist does not tie must be such that $\pi_M \geq \pi_M^*$. Further, one equilibrium to the resulting subgame is that the monopolist charges V_A-c_c for the primary product, c_c for its complementary product, the alternative producer charges c_c for its complementary product, and consumers in the first period purchase primary units from the monopolist and complementary units from the alternative producer (this again is equilibrium behavior since each firm's pricing strategy is a best

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[32] See Choi (1996,2004) for previous analyses of the effects of tying on R&D incentives.

response to the other firm's pricing strategy). This yields the monopolist $\pi_M=\pi_M{}^*+N(V_A-V_M)$. Notice that since it is possible that the monopolist correctly anticipates that this will be the equilibrium if the monopolist does not tie, one equilibrium to the full game is characterized by the monopolist not tying and $\pi_M>\pi_M{}^*$. Further, using a similar argument one can show there are other equilibria of this sort. Hence, there exist equilibria in which $\pi_M>\pi_M{}^*$.

Proof of Lemma 1: Consider period 2. Suppose the alternative producer does not invest. Then its second-period profit equals zero. Suppose only the alternative producer invests. Then the alternative producer charges a second-period price for its upgraded complementary good equal to λ, earns second-period profit equal to $N(\lambda-c_c)-R$, and the monopolist earns second-period profit equal to zero. Suppose both firms invest. Bertrand competition means that the monopolist charges c_c for its upgraded complementary good, the alternative producer charges λ ($c_c+V_A-V_M$) if $V_M+\lambda-V_A\leq(>)c_c$ for its upgraded complementary good, consumers purchase the alternative producer's upgraded complementary good, the alternative producer earns second-period profit equal to $N(\lambda-c_c)-R$ ($N(V_A-V_M)-R$) if $V_M+\lambda-V_A\leq(>)c_c$, and the monopolist earns second-period profit equal to $-R$. Suppose $V_A>V_M+(R/N)=V_A{}^*$. Then the above yields the alternative producer must invest. But if the monopolist anticipates the alternative producer will invest, then the monopolist will not and i), ii), and iii) hold.

Proof of Proposition 2: Suppose the monopolist ties. Then the alternative producer cannot sell complementary units in either period and so it does not invest at the beginning of the second period. This means the monopolist sells new tied units at the beginning of the first period at a price equal to $2V_M$, it invests R in the second period and then sells upgraded complementary units at a price λ, and its overall profit equals $N[2V_M+\lambda-c_p-2c_c]-R$.

Now suppose the monopolist does not tie. Given $V_A>V_A{}^*$, we know that if consumers purchase primary units from the monopolist and complementary units from the alternative producer in the first period, then i) through iii) of Lemma 1 holds. Given the constraint that prices must be non-negative we have that the monopolist's first-period price for its primary product cannot exceed $2V_A$, but this means its overall profit must be less than or equal to $N[2V_A-c_p]$. But comparing this expression with the profit expression given tying yields that, if λ is sufficiently large and $V_A>V_A{}^*$, then the monopolist will tie if it anticipates that in the first period consumers will purchase primary units from the monopolist and complementary units from the alternative producer.

Now consider the first period. If the monopolist does not sell primary units in the first period, then its overall profit is less than the profit it earns by tying so it would be better off tying. If the monopolist sells primary units in the first period but no one sells complementary units, then again its overall profit is less than the profit it earns by tying so it would be better off tying.

The only other possibility is that the monopolist sells primary and complementary units in the first period. Given our assumption that prices cannot be strictly negative, at any pair of first-period prices for which the monopolist might plausibly sell primary and complementary units, the alternative producer can set a first-period price of zero, sell complementary units in the first period, and earn overall profit equal to $N[\lambda-2c_c]-R$ which is strictly positive for λ sufficiently large. Hence, if λ is sufficiently large, in the first period the monopolist sells primary units and the alternative producer sells complementary units. Combining this with results above, we now have that if λ is sufficiently large and $V_A>V_A*$, then i) through iii) hold.

Finally, we have shown that, if λ is sufficiently large and $V_A>V_A*$, then the only difference from a social-welfare standpoint between the monopolist being allowed to tie and not being allowed to tie is that individuals consume the monopolist's lower quality complementary products when the monopolist is allowed to tie and the alternative producer's higher quality complementary products when it is not allowed to tie. Hence, if λ is sufficiently large and $V_A>V_A*$, then $W<W^N$.

Proof of Proposition 3: Suppose first that the monopolist ties and sells its products. Then the alternative producer is not able to sell or lease its complementary product. Because consumers are identical and $N\lambda>R+Nc_c$, in this case equilibrium behavior is that the monopolist charges $2V_M$ for the tied product in the first period, the monopolist invests and sells an upgraded complementary product in the second period for λ, and consumers purchase the tied product from the monopolist in the first period and the upgraded complementary product from the monopolist in the second period. This yields monopoly profits the same as if there were no alternative producer, i.e., $\pi_M=\pi_M*=N[2V_M+\lambda-c_p-2c_c]-R$.

Suppose now that the monopolist ties and leases its products. Then again the alternative producer is not able to sell or lease its complementary product. Because consumers are identical and $N\lambda>R+Nc_c$, in this case equilibrium behavior is that the monopolist charges V_M for the tied product in the first period, the monopolist invests and leases an upgraded tied product in the second period for $V_M+\lambda$, and consumers lease the tied product from the monopolist in the first period and the upgraded tied product from the monopolist in the second period. This also yields monopoly profits the same as if there were no alternative producer, i.e., $\pi_M=\pi_M*=N[2V_M+\lambda-c_p-2c_c]-R$.

We now consider what happens when the monopolist does not tie. Let us start by considering period 2 in the case in which both firms leased in the first period. One equilibrium to the resulting second-period subgame is that only the alternative producer invests, the monopolist charges $V_M+\lambda-c_c-(R/N)$ for the primary product, $c_c+\varepsilon$ for its complementary product, the alternative producer charges $V_A-V_M+c_c+(R/N)$ for its complementary product, and consumers lease primary units from the monopolist and upgraded complementary units from the alternative producer (one reason this is equilibrium behavior is that, if the monopolist chose to invest, then there is necessarily an equilibrium to the second-period

pricing game in which second-period monopoly profits are no higher). This yields second-period profits for the monopolist equal to $N[V_M+\lambda-c_c]-R$.

Now consider what happens in period 1 if at the beginning of the period both firms choose to lease. Suppose that for any set of first-period behaviors the equilibrium to the second-period subgame is the one described above in which the monopolist earns second-period profits equal to $N[V_M+\lambda-c_c]-R$. Given this, one equilibrium set of first-period behaviors is that the monopolist charges V_M-c_c for the primary product, $c_c+\varepsilon$ for its complementary product, the alternative producer charges $V_A-V_M+c_c$ for its complementary product, and consumers lease primary units from the monopolist and complementary units from the alternative producer. This is an equilibrium set of first-period behaviors in that each firm's choice maximizes its profits over the two periods given the other firm's pricing behavior. This yields first-period profit for the monopolist equal to $N[V_M-c_p-c_c]$ and profit over the two periods equal to $N[2V_M+\lambda-c_p-2c_c]-R$.

We now have that one equilibrium to the subgame that starts after the monopolist chooses not to tie and both firms choose to lease has $\pi_M=\pi_M^*=N[2V_M+\lambda-c_p-2c_c]-R$. But similar arguments yield that for each of the other three possibilities associated with the monopolist choosing not to tie, i.e., both firms sell, the monopolist leases and the alternative producer sells, and the monopolist sells and the alternative producer leases, there is an equilibrium to the resulting subgame for which $\pi_M=\pi_M^*$. Given this, suppose the monopolist anticipates that if it chooses not to tie the equilibrium for each possible subgame is the one that results in $\pi_M=\pi_M^*$. Then the monopolist maximizes its profits by tying which means, given the above, there is an equilibrium with tying and leasing and an equilibrium with tying and selling and in both cases $\pi_M=\pi_M^*$.

Suppose again the monopolist does not tie. Since the monopolist had the option of tying and earning π_M^*, any equilibrium in which the monopolist does not tie must be such that $\pi_M\geq\pi_M^*$. Given this, consider first period 2. It is always the case that an equilibrium to the subgame starting in the second period is that only the alternative producer invests, pricing is such that the alternative producer earns second-period profits equal to zero, and the monopolist receives the remaining second-period surplus (which must be strictly positive given our parameter restrictions). This is an equilibrium because the monopolist cannot possibly receive more by investing, while for any possible starting second-period situation not investing can result in profit for the alternative producer less than or equal to zero.

Given this, consider the first period and suppose that, for any first period set of behaviors, the equilibrium to the second-period subgame is the one described above in which the alternative producer invests and earns zero profits. Then the alternative producer's first-period behavior will maximize first-period profits. Taking all this as given, one equilibrium set of behaviors for the first period is that both firms lease, the monopolist charges V_A-c_c for its primary product, $c_c+\varepsilon$ for its complementary product, the alternative producer charges c_c for its complementary product, and consumers lease primary units from the monopolist and complementary units from the alternative producer.

This is equilibrium first-period behavior because over the two periods the monopolist is earning all the potential surplus so there cannot be an alternative first-period behavior for the monopolist that is better, while given the monopolist's first-period strategy there is no alternative behavior for the alternative producer that yields strictly positive profits over the two periods. This shows that there is one equilibrium to the full game characterized by the monopolist not tying and $\pi_M > \pi_M^*$. Further, using a similar argument one can show that there are other equilibria of this sort. Hence, there exist equilibria in which the monopolist does not tie and $\pi_M > \pi_M^*$.

Proof of Lemma 2: There are four possibilities. The first is that both firms invest. Given our assumption that the surplus is split evenly across the two firms, we have that the monopolist prices the primary good at $V_M + \lambda - c_c + [(V_A - V_M + \Delta)/2]$, the alternative producer prices its upgraded complementary good at $[(V_A - V_M + \Delta)/2] + c_c$, and consumers lease the primary good from the monopolist and the upgraded complementary good from the alternative producer (the monopolist prices its upgraded complementary good high enough that this price does not serve as a constraint on the price the alternative producer charges for its upgraded complementary good). This yields second-period profits for the monopolist equal to $N[V_M + \lambda - c_c + [(V_A - V_M + \Delta)/2]] - R$ and second-period profits for the alternative producer equal to $N[(V_A - V_M + \Delta)/2] - R$.

The second possibility is that neither firm invests. Given our assumption that the surplus is split evenly across the two firms, we have that the monopolist prices the primary product at $V_M + [(V_A - V_M + \Delta)/2]$, the alternative producer prices its complementary good at $[(V_A - V_M + \Delta)/2]$, and consumers lease the primary good from the monopolist and the complementary good from the alternative producer (as before, the monopolist's complementary-good price is high enough that it does not serve as a constraint). This yields second-period profits for the monopolist equal to $N[V_M + [(V_A - V_M + \Delta)/2]]$ and second-period profits for the alternative producer equal to $N[(V_A - V_M + \Delta)/2]]$

The third possibility is that the alternative producer invests and the monopolist does not. Given our assumption that the surplus is split evenly across the two firms, we have that the monopolist prices the primary product at $V_M + [(V_A - V_M + (\lambda - c_c) + \Delta)/2]$, the alternative producer prices its upgraded complementary good at $[(V_A - V_M + (\lambda - c_c) + \Delta)/2] + c_c$, and consumers lease the primary good from the monopolist and the upgraded complementary good from the alternative producer (as before, the monopolist's complementary-good price is high enough that it does not serve as a constraint). This yields second-period profits for the monopolist equal to $N[V_M + [(V_A - V_M + (\lambda - c_c) + \Delta)/2]$ and second-period profits for the alternative producer equal to $N[(V_A - V_M + (\lambda - c_c) + \Delta)/2] - R$.

The fourth possibility is that the monopolist invests and the alternative producer does not. There are two subcases. The first subcase is that $V_A \leq V_M + (\lambda - c_c) - \Delta$. In this subcase the alternative producer does not lease or sell anything in the second period so the firm's second-period profit equals zero (when

$V_A=V_M+(\lambda-c_c)-\Delta$ the alternative producer might lease or sell complementary units in the second period but second-period profit still equals zero).

The second subcase is that $V_A>V_M+(\lambda-c_c)-\Delta$. Given our assumption that the surplus is split evenly across the two firms, in this case we have that the monopolist prices the primary product at $V_M+\lambda+[(V_A-V_M-(\lambda-c_c)+\Delta)/2]$, the alternative producer prices its complementary good at $[(V_A-V_M-(\lambda-c_c)+\Delta)/2]$, and consumers lease the primary good from the monopolist and the complementary good from the alternative producer (as before, the monopolist's complementary-good price is high enough that it does not serve as a constraint). This yields second-period profits for the monopolist equal to $N[V_M+\lambda-c_c+[(V_A-V_M-(\lambda-c_c)+\Delta)/2]-R$ and second-period profits for the alternative producer equal to $N[(V_A-V_M-(\lambda-c_c)+\Delta)/2]$.

Consider first the investment decision. Suppose the alternative producer thinks the monopolist will not invest. Then from above the return to the alternative producer investing is $[N(\lambda-c_c)/2]-R>0$ so the alternative producer invests (see footnote 22). Suppose the alternative producer thinks the monopolist will invest. Then from above the return to the alternative producer investing is greater than or equal to $\min\{[N(\lambda-c_c)/2]-R,N(V_A-V_M+\Delta)/2]-R\}>0$ so the alternative producer invests (see again footnote 22). That is, the alternative producer invests independent of whether or not it thinks the monopolist will invest. Now consider the monopolist's choice given it knows that the alternative producer will invest. Then from above the return to the monopolist investing is $[N(\lambda-c_c)/2]-R>0$, so the monopolist invests (see again footnote 22). Thus, both firms invest. This directly proves i) and ii), and then iii) and iv) follow from above.

Proof of Proposition 4: Suppose the monopolist ties and leases. Then in the first period it leases its tied product for V_M and earns $N[V_M-c_p-c_c]$. Given our parameter restrictions, in the second period the monopolist invests and the alternative producer does not, the monopolist leases the upgraded tied product for $V_M+\lambda+\Delta$, and the monopolist earns $N[V_M+\lambda+\Delta-c_c]-R$. The monopolist's profit over the two periods is $N[2V_M+\lambda+\Delta-c_p-2c_c]-R$.

Now suppose the monopolist ties and sells. Then in the first period it sells its tied product for $2V_M+\Delta$ and earns $N[2V_M+\Delta-c_p-c_c]$. Given our parameter restrictions, in the second period the monopolist invests and the alternative producer does not, the monopolist sells the upgraded complementary product for λ, and the monopolist earns $N[\lambda-c_c]-R$. The monopolist's profit over the two periods is again $N[2V_M+\lambda+\Delta-c_p-2c_c]-R$.

Now suppose the monopolist does not tie. We first consider what happens when the monopolist does not tie and leases its products. We start by considering the second period. There are three possibilities concerning what is true at the beginning of the second period. The first possibility is that the monopolist leased primary and complementary units in the first period. If λ and Δ are both sufficiently large, then in the second period only the monopolist invests, the monopolist leases primary and

complementary units for a combined price of $V_M+\lambda+\Delta$, the monopolist earns second-period profits equal to $N[V_M+\lambda+\Delta-c_c]-R$, and the alternative producer earns second-period profits equal to zero. The second possibility is that the monopolist leased primary units and the alternative producer leased complementary units in the first period. If λ and Δ are both sufficiently large, then in the second period both firms invest, the monopolist leases primary units and the alternative producer leases complementary units, and the alternative producer's profit equals $N[(V_A-V_M+\Delta)/2]-R$. The third possibility is that the monopolist leased primary units and the alternative producer sold complementary units in the first period. The details of what happens in this case are not required for our argument.

Now consider the first period. If individuals consume the monopolist's complementary product and λ and Δ are both sufficiently large, then we know the alternative producer earns zero over the two periods. Suppose the alternative producer offers to lease its complementary product at a price of zero in the first period. Because prices cannot be strictly negative and the alternative producer has a superior complementary product, this must result in consumers leasing complementary units from the alternative producer. Given the above, this means profits over the two periods for the alternative producer must be at least equal to $N[((V_A-V_M+\Delta)/2)-c_c]-R$. But given the participation constraint for consumers, we now have that monopoly profits over the two periods must be less than or equal to $N[2V_A+\lambda+\Delta-c_p-2c_c]-R-[N[((V_A-V_M+\Delta)/2)-c_c]-R]$. If Δ is sufficiently large, we now have that the monopolist is better off tying and either selling or leasing.

Now suppose the monopolist does not tie and sells its products. We again start by considering the second period. There are again three possibilities concerning what is true at the beginning of the second period. The first possibility is that the monopolist sold primary and complementary units in the first period. If λ and Δ are both sufficiently large, then in the second period only the monopolist invests, the monopolist sells upgraded complementary units at λ, the monopolist earns second-period profits equal to $N(\lambda-c_c)-R$, and the alternative producer earns second-period profits equal to zero. The second possibility is that the monopolist sold primary units and the alternative producer sold complementary units in the first period. If λ and Δ are both sufficiently large, then in the second period only the alternative producer invests, the alternative producer sells upgraded complementary units at λ, the alternative producer earns second-period profits equal to $N(\lambda-c_c)-R$, and the monopolist's second-period profit equals zero. The third possibility is that the monopolist sold primary units and the alternative producer leased complementary units in the first period. If λ and Δ are both sufficiently large, then in the second period only the alternative producer upgrades, the alternative producer leases upgraded complementary units, the alternative producer earns second-period profits equal to $N[V_A-V_M+\lambda+\Delta]-R$, and the monopolist's second-period profit equals zero.

Now consider the first period. If individuals consume the monopolist's complementary product and λ and Δ are both sufficiently large, then we know the alternative producer earns zero profits over the two periods. Suppose the alternative producer offers to sell its complementary product at a price of zero

in the first period. Because prices cannot be strictly negative and the alternative producer has a superior complementary product, this must result in consumers purchasing complementary units from the alternative producer. Given the above, this means profits over the two periods for the alternative producer must be at least equal to $N(\lambda-2c_c)$-R. But given the participation constraint for consumers, we now have that monopoly profits over the two periods must be less than or equal to $N[2V_A+\lambda+\Delta-c_p-2c_c]$-R-$[N(\lambda-2c_c)$-R]. If λ is sufficiently large, we now have that the monopolist is better off tying and either selling or leasing.

Finally, from above we have that, if λ and Δ are both sufficiently large and the monopolist does not tie, then individuals consume the alternative producer's complementary product in the first period and the upgraded complementary product in the second period. Relative to what happens under tying, this improves social welfare by $2N(V_A-V_M)$. The only potential decrease in social welfare is that both firms rather than one firm invests which would lower social welfare by R. If $2N(V_A-V_M)$>R, then the increase dominates, i.e., $W<W^N$.

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