UPGRADES, SWITCHING COSTS AND THE LEVERAGE THEORY OF TYING*

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This article investigates the role of product upgrades and consumer switching costs in the tying of complementary products. Previous analyses have found that a monopolist of one product will not increase its profits and reduce social welfare by tying and leveraging its monopoly position into a complementary market if the initial monopolised product is essential, where essential means that all uses of the complementary good require the initial monopolised product. We show that this is not true in settings characterised by product upgrades and consumer switching costs. We also discuss various extensions including the role of the reversibility of tying.

Despite the increased interest in tie-in sales stimulated in part by Microsoft’s tying of Internet Explorer with its Windows operating system and the subsequent US anti-trust case, little research has examined tying when product upgrades are important.¹ This is quite odd because many tie-ins such as most of Microsoft’s tie-ins of applications software with its operating system involve goods that are periodically upgraded. This article shows that upgrades create an incentive to tie in a broader set of circumstances than is suggested by previous literature. Whinston’s (1990) classic paper on tying derived conditions under which tying used to extend market power is not profitable. This article shows that when upgrading is important tying used to extend market power can be profitable even when those conditions are satisfied. Moreover, this article provides an explanation for examples of Microsoft’s tying of applications programs with its operating system and related behaviour that previous theory has trouble explaining. Finally, this article provides a new rationale for leasing.

In the leverage theory of tying, a monopolist in one market ties a complementary good in which there are rival producers to extend its market power to the tied-good market.²

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¹ Carlton has consulted both for and against Microsoft. Waldman has consulted for Microsoft.

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. The definition of the terms ‘leverage’ and ‘extend monopoly’ is often not precise. In the academic legal literature in anti-trust the words ‘leverage’ and ‘extend monopoly’ have a negative connotation and are often used synonymously to mean illegal activity. In that literature, one can often usefully distinguish between the extraction of surplus (as for example occurs with price discrimination, a practice that is typically legal under antitrust laws) and the creation of new deadweight loss from the creation or maintenance of market power, practices that may not be legal under antitrust laws — see Carlton and Heyer (2008) for a discussion. In this article, we use the words ‘leverage’ and ‘extend monopoly’ in the manner they are often used in the economics literature, not to ask whether the conduct should be illegal but rather to ask under what circumstances the conduct is profit maximising and what the welfare effect of the practices are. We only briefly touch on anti-trust implications. For a discussion of our views of the relevant antitrust issues see Carlton and Heyer (2008) and Carlton et al. (2008). For those who have followed the legal academic literature on this topic, we think the word ‘extraction’ better describes the behaviour in this article than the words ‘leverage’ or ‘extend monopoly’.

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Starting in the 1950s, authors typically associated with the Chicago School argued that in the common case of fixed proportions in consumption between the tied and tying goods the leverage theory of tying is never valid because a monopolist can always extract all potential profits from its original monopoly position without tying (Director and Levi, 1956; Bowman, 1957; Posner, 1976; Bork, 1978). To see their logic, consider the profitability of a monopolist of shoes versus the profitability of a right-shoe monopolist when left shoes are competitively supplied. If $P^*$ is the optimal monopoly price for a pair of shoes and $P_L$ the competitive price for left shoes, then a right-shoe monopolist can sell right shoes for $P^*/C_0P_L$ and earn the profitability associated with tying and selling a pair of shoes at $P^*$.

In an important paper, Whinston (1990) formally considers the Chicago School argument in a one-period setting and shows it holds under some conditions but not all – see also Ordover et al. (1985). In particular, Whinston shows the argument is correct when the monopolist’s primary product is essential, that is, all uses of the complementary good require the monopolist’s primary good. In contrast, when the primary product is not essential and where constant returns to scale and competition are lacking in the tied-good market, tying can sometimes increase monopoly profits by extending its market power to the tied-good market. From the standpoint of applying the leverage theory of tying to Microsoft’s actions, these results are problematic. For many of the applications programs that Microsoft has bundled with Windows, the Windows operating system seems to be essential or close to it, and thus Whinston’s results suggest that the leverage theory of tying cannot provide a rationale for why Microsoft has chosen to bundle applications programs with Windows. So the question remains, is it the case that Microsoft’s bundling of applications programs with Windows has nothing to do with leveraging or extending market power?

One approach to answering this question is to relax the assumption that the primary good is essential by introducing the possibility of entry into the primary-good market. Then, it is possible that tying can be used to preserve or extend a monopoly position in the tying market. We analysed this possibility in Carlton and Waldman (2002). There we considered a series of models, characterised by either entry costs or network externalities that show how a monopolist can use tying to both preserve and extend monopoly positions in the tying good.3

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, as argued by the US Justice Department, technological conditions in the browser case were such that a successful rival browser had the potential to evolve into a substitute for Windows. So our explanation of tying used to protect the primary-market monopoly is plausible for that case. But such conditions do not hold generally

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3 Other related papers based on entry deterrence include Choi and Stefanadis (2001) and Nalebuff (2004). The former shows how tying by an incumbent producer in two complementary markets can preserve a monopoly by reducing the probability of entry in each market, while the latter shows how tying can deter entry in a model where goods are independent – Whinston (1990) also considers a setting where tying is used to deter entry in a model with independent products. Neither of these papers shows why a monopolist of an essential good would tie. Also, another possibility is that Microsoft is responding to efficiency considerations. See Carlton and Perloff (2005), Evans and Salinger (2005, 2008) and Carlton and Waldman (2010) for recent discussions of efficiency rationales for tying.
for applications programs. For example, no one argues that a successful rival to Windows Media Player has the potential to evolve into a rival to Windows and yet Microsoft has frequently bundled a digital media player with its Windows operating system.\(^4\) So protecting the primary-market monopoly is not a general explanation for Microsoft’s tying decisions regarding applications programs.

Given that current theory concerning tying and extending market power seems not to apply to many of Microsoft’s tying decisions regarding applications programs,\(^5\) we re-examine the question initially considered by Whinston which is, under what circumstances will a firm that produces a monopolised primary product tie a complementary product to leverage or extend its monopoly into the tied-good market? We show that because of the sequential nature of trade, if upgrades are important for the complementary product, then a primary-good monopolist may indeed tie to monopolise a complementary market even when the monopolist’s primary product is essential. We further show that the incentive to tie becomes even stronger when the complementary product is also characterised by switching costs (note that upgrades and switching costs are clearly associated with many of Microsoft’s applications programs).\(^6\) Thus, Whinston’s results concerning when tying is not profitable in a one-period setting do not apply in our multi-period setting involving upgrades.

Our analysis reveals that an implicit assumption in Whinston’s analysis is that all relevant sales take place simultaneously. This is a reasonable assumption for many products but not when upgrades are important. 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, as Whinston shows, appropriately choosing prices for individual products ensures the firm does at least as well as with tying. But this is not the case when some sales occur in a later period and in the first period the monopolist cannot commit to actions for this later period. In our analysis, because upgrades are sold later, the monopolist has limited ability to capture profits associated with upgrading by selling individual products and simply choosing appropriate period-1 prices for the individual products. Rather, if the firm sells its products and there are upgrade profits, the only way the monopolist can ensure that it captures the upgrade profits is by selling the upgrades. The result is that when upgrade profits are large there can be an incentive for the monopolist to tie even though in our model the monopolist’s complementary product is inferior to the rival’s. In short, tie-in sales are a way – though not necessarily a socially efficient way – for the monopolist to commit to future actions. Also, although we do not show it formally, there are settings other than those characterised by upgrades where our basic logic applies such as when there is a new complementary good that only becomes available in a later period.

\(^4\) Microsoft’s tying of Windows Media Player with Windows was a subject of the European Union Microsoft competition case started in 1993 which focused on Microsoft’s potential abuse of its dominant position.

\(^5\) In addition to Internet Explorer and Windows Media Player, other applications bundled with the current version of Windows, Windows 7, include Windows Media Center, Windows DVD Maker, WordPad, Calculator and Sticky Notes. Other than Internet Explorer, our belief is that in none of these cases is Microsoft’s decision to tie the application program plausibly explained by a desire to protect the Windows monopoly.

\(^6\) There is an extensive literature concerning consumer switching costs. See Klempner (1995) and Farrell and Klempner (2007) for surveys. Probably the closest related paper in this literature is Klempner (1987) which considers entry deterrence in the context of switching costs but that paper does not consider the role of tying. There is also a small literature concerning the upgrade process. See, for example, Fudenberg and Tirole (1998) and related analyses in Waldman (1996), Lee and Lee (1998) and Fishman and Rob (2000).
Again, the key to our argument is that some sales occur in a later period and commitment is not possible.

In addition to the main analyses discussed above, we also consider a number of extensions including whether ties are reversible, that is, when the monopolist ties can a consumer of the monopolist’s product use the rival’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 costlessly reversible, in contrast, tying is equivalent to setting the price of the complementary good to zero so there is no incremental return to tying. We relate this result to Microsoft’s behaviour in the design of Windows.

There are a number of arguments in the literature where a primary-good monopolist ties a complementary good even when the primary good is essential but these arguments are not examples of what economists usually describe as the leverage theory of tying. First, in the metering explanation for tie-in sales (Chen and Ross, 1993; Klein, 1993) the tie-in is used to price discriminate in the primary-good market rather than create and exploit market power in the complementary-good market. Second, the ‘surprise theory’ of aftermarket monopolisation (see Shapiro, 1995 for a discussion) and related arguments such as the one put forth in Borenstein et al. (1995) are not about leverage but rather about firms taking advantage of consumer lock-in associated with the purchase of a durable good. Third, building on the analysis in Farrell and Katz (2000), Carlton et al. (2010) and Miao (2010) show that tying can be used to facilitate a price squeeze which transfers profits from a complementary-good rival to the monopolist of a primary good. But these analyses are not about leverage because the main return to tying in these analyses is to transfer profits not reduce or eliminate competition. Fourth, Choi (2010) considers tying by a monopoly seller of an essential good in a two-sided market. The tying increases monopoly profits but this model is also not an example of the leverage theory of tying as tying in this model does not eliminate competition in the tied-good market.

Other related analyses include Chen and Nalebuff (2006) and Ordover and Shaffer (2007). In Chen and Nalebuff’s analysis there is a monopolist of an essential primary good and a complementary good monopolised by a rival, where the complementary good is not essential for the use of the primary good. They show various strategies the primary-good monopolist can employ to squeeze the rival but creating a substitute complementary good and tying does not increase profitability. Ordover and Shaffer consider how below marginal cost pricing can be used for exclusion in a world characterised by switching costs. There are some similarities between that paper’s analysis and our analysis in Section 3, but tying does not increase monopoly profitability in their setting.

As already discussed in footnote 2, the precise definition of ‘the leverage theory’ is often unclear especially when one compares the legal and economic literatures. We use ‘the leverage theory’ here to mean the creation of market power in the complementary good market, typically by harming or eliminating a rival, but we caution the reader not to pay too much attention to labels. Regardless of how one labels the conduct, it is possible to calculate the effects on prices and social welfare. Our theory extends the tying literature by examining tying in a dynamic context where the complementary good is improved over time.

This article also contributes to the related literature on systems competition and, in particular, the choice for a firm to have an open or a closed system (Matutes and Regibeau, 1988; Kende, 1998; Church and Gandal, 2000; Tag, 2008). In the literature on systems competition, firms sell or lease systems which consist of primary or platform goods and complementary goods. A main focus of that literature is whether a firm selling a primary good should allow its system to be open or closed, where an open (closed) system is one that can (cannot) be used with a rival’s complementary good. Choosing whether to have an open or a closed system is analogous to the choice in the tying literature between selling products individually and using an irreversible tie. Given this, Whinston’s (1990) analysis can be interpreted to say that a monopolist of an essential primary good will always choose to have an open system. While our analysis is consistent with this result for one-period models, it shows that in multi-period models, if primary and complementary units are not sold simultaneously due, for example, to complementary-good upgrades, closed systems can be preferred even when the monopolist’s primary good is essential. The reason is that having a closed system can be a way for the monopolist to commit – possibly an inefficient way to commit – to future actions.

As a final introductory point, although much of the current attention given to tying arrangements stems from the Microsoft cases and Microsoft’s behaviour, there are numerous other examples of firms that tie and in many of these other cases upgrades are common. For example, in the 1960s IBM tied software and services with its marketing of mainframe computers and the software was periodically upgraded. Prior to its decision in 1969 to untie many of these products, IBM’s practices concerning tying were an important focus of antitrust debates (for discussions of IBM’s behaviour see Soma, 1976; Fisher et al., 1983). Another more recent example is Siemens’ marketing of CT scanners which include diagnostic imaging systems for which periodic upgrades are typically available.

The outline for the article is as follows. Section 1 considers a model characterised by upgrades but no switching costs and shows that tying can be optimal when firms only sell their products. Section 2 incorporates switching costs and shows that tying can be optimal given selling or leasing. Section 3 considers three extensions: reversible ties; negative prices; and primary good upgrades. Section 4 presents concluding remarks.

1. Tying in the Presence of Complementary-Goods Upgrades

This Section analyses what happens when there are upgrades for the complementary product but no switching costs. We show that, if the monopolist sells its products, the monopolist sometimes ties to capture potential profits associated with upgrading. However, we also show tying is not useful if leasing is possible. The following Section introduces consumer switching costs.

1.1. The Model

We consider a two-period setting in which the monopolist is the sole producer of the primary product, say due to patenting, where the monopolist has a constant marginal
cost for producing this good, denoted $c_p$. There is a complementary good that can be produced by the monopolist and a single rival, where the monopolist and the rival have the same constant marginal cost for producing the complementary good, denoted $c_c$. However, as described in more detail below, the rival’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 period 2, each firm has the option of investing $Z, Z > 0$, and then selling higher quality complementary units in period 2. 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 or a complementary unit by itself. To be precise, in period 1 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 rival is $V_R$ where $V_R > V_M$ captures that the rival’s product is higher quality. Similar results would be found if we assumed that the rival had a lower cost for producing the complementary good rather than a higher quality complementary good. Results would also be similar if we assumed that the higher quality or lower cost only applied to the rival’s period-2 complementary good as opposed to our assumption that it applies to both period-1 and period-2 complementary goods. We also assume $2V_M > c_p + c_c$ to ensure production is profitable (note this is the correct condition because the goods are durable and as indicated below there is no discounting).

If an individual consumes a system in period 2 that contains the monopolist’s complementary product, then he receives $V_M$ if it is not upgraded and $V_M + \lambda$ if it is, where $N\lambda > Z + Nc_c \ (N\lambda > Z + Nc_c \ means \ upgrading \ is \ efficient)$. On the other hand, if an individual consumes a system in period 2 that contains the rival’s complementary product, then he receives $V_R$ if it is not upgraded and $V_R + \lambda$ if it is. In this specification, $\lambda$ is the added benefit of consuming an upgraded product. Also, in this model the gross benefit an individual receives from consuming a system in period 2 is independent of what the individual consumed in period 1.

Since in our model there is no reason for the monopolist to offer both tied and individual products because consumers are identical (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), in the beginning of period 1 the monopolist decides whether to offer a tied product consisting of one unit of its primary and complementary goods or whether to offer individual products. Following Whinston (1990), we begin by assuming ties are irreversible. That is, if a consumer purchases a tied good from the monopolist, the consumer cannot add the rival’s complementary good to the system. As a result, if the monopolist ties, the rival does not sell any complementary units. An irreversible tie is like the monopolist

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*Because our models are characterised 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 early analyses of this issue. Also, see later in this Section and footnote 23 for further discussion of what happens if consumer heterogeneity is introduced.*

offering a primary product that is incompatible with the rival’s complementary good, while a reversible tie is like the monopolist offering a primary product that is compatible with the rival’s complementary good. Note, even though in our model ties are irreversible, a consumer who purchases the monopolist’s tied product in period 1 can add the monopolist’s upgraded product to his system in period 2.

We also adopt the following assumptions. First, there is no discounting by either firms or consumers, where the no discounting assumption should be interpreted as no discounting and periods of equal length. Allowing discounting or periods of different lengths would complicate the analysis but would not change the qualitative nature of the results. Second, if a consumer purchases a complementary unit in period 1 and then purchases an upgraded complementary unit in period 2, the used complementary good has no scrap value and there is no secondhand market in which to sell the used good. Introducing a secondhand market would not change any of the results because of our assumption that all consumers are identical, while introducing a positive scrap value would also not substantially change our results. Third, following Fudenberg and Tirole (1998), when selling upgrades firms can price discriminate. That is, a firm can 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. A firm cannot price discriminate in this way when there is competition and products are homogeneous. But this type of price discrimination is sometimes feasible in our analysis because products are not homogeneous, for example, it is feasible for the rival when the rival upgrades and the monopolist does not. Fourth, we restrict attention to Pure-Strategy Subgame-Perfect Nash equilibria and to symmetric equilibria, that is, equilibria in which each of the \( N \) identical consumers employs the same equilibrium strategy; we also assume consumers purchase or lease the rival’s complementary good when they are indifferent between the two complementary goods.

Note that in this model, in the absence of tying, there are typically multiple equilibria which differ in terms of the manner in which the surplus associated with the rival’s complementary product is divided between the monopolist and the rival. Our main results would not qualitatively change if we focused on a particular equilibrium such as the one in which this surplus is divided equally between the monopolist and the rival – this would be the unique equilibrium if a slight amount of noise were added to the model. In this Section, we intentionally allow for multiple equilibria in the absence of tying because we want to show that our main results hold independently of how this multiple equilibria problem is resolved. In the next Section, however, we do impose a surplus sharing assumption.

The timing of decisions is as follows. Period 1 consists of three stages. First, the monopolist chooses whether to have tied or individual products. Second, the firms simultaneously 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.\textsuperscript{10} Third, consumers then simultaneously choose which products to purchase (or lease when products are offered for lease). Period 2 then consists of three stages. First, firms simultaneously choose whether to invest $Z$ and upgrade their complementary products. Second, firms simultaneously choose prices. Third, consumers simultaneously choose which products to purchase (or lease when products are offered for lease). Note, if the monopolist leases $N$ primary units in period 1, then it incurs no period-2 production cost if it leases $N$ primary units in period 2 (and similarly a firm that leases $N$ complementary units in period 1 incurs no period-2 production costs if it does not upgrade and leases $N$ complementary units in period 2).

1.2. Selling Only

In this subsection, we analyse the model when firms only sell their products, where one reason this could be the case is that there is a moral-hazard problem associated with leasing, as in Henderson and Ioannides (1983), Smith and Wakeman (1985) and Mann (1992). Our main result is that, if firms are restricted to selling, then upgrades make tying a valuable tool. In particular, the monopolist ties when the incremental benefit associated with consuming an upgraded product and the extra quality associated with the rival's superior complementary product are both high.

We begin with a benchmark analysis in which there are no upgrades, i.e., \( \lambda = 0 \). Our argument in this 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. We show the same result holds in our model in the absence of upgrades.

**Proposition 1.** Suppose firms sell their products and there are no upgrades, i.e., \( \lambda = 0 \). Then there are multiple equilibria, where in one equilibrium the monopolist ties while in the other equilibria it sells individual products. In the tying equilibrium monopoly profitability equals monopoly profitability in the absence of a rival, while in the other equilibria monopoly profitability is greater than or equal to monopoly profitability in the absence of a rival (where in some of these the inequality is strict).

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

\textsuperscript{10} We assume the monopolist either sells both products or leases both products, that is, 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 period-1 decision concerning selling or leasing is also binding for period 2. This entails no loss of generality because in our model there is no real difference between selling and leasing in period 2.

The logic for this finding is the same as Whinston’s argument referred to above. Suppose for a moment there is no rival. 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 there is a rival and the monopolist does not tie. As the monopolist can guarantee itself tying profits by setting the prices for the primary and complementary goods as before, it follows that the presence of the rival cannot hurt monopoly profitability. Hence, in this case the monopolist may hurt profitability and cannot help profitability by tying. Or to put this more simply, if there are no upgrades, then all transactions occur in period 1. In turn, as all sales occur simultaneously, then Whinston’s logic applies.

One final comment about Proposition 1 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 characterised by consumers purchasing the monopolist’s primary good and the rival’s complementary good. What varies across these equilibria is how the surplus associated with the rival’s superior complementary product is shared between the firms. Any sharing rule between all the surplus being received by the monopolist and all being received by the rival is possible. In the tying equilibrium, the monopolist anticipates that if it sold individual products it would receive none of the 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 a strictly positive share 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, that is, $\lambda$ is sufficiently large that upgrading occurs in equilibrium. This case works quite differently than the benchmark case analysed above. The reason is that because of the sequential nature of trade the monopolist can no longer sell individual products and guarantee itself profits at least as high as under tying.

We begin our analysis of this case by considering behaviour in period 2 as a function of what happens in period 1. We partially characterise this in Lemma 1.

**Lemma 1.** Suppose all consumers in period 1 purchase the monopolist’s primary good and the rival’s complementary good. Holding all other parameters fixed, if the added benefit of consuming the rival’s rather than the monopolist’s complementary good exceeds the research and development cost, i.e., $V_R - V_M > Z/N$, then (i), (ii) and (iii) characterise behaviour in period 2.

(i) Only the rival invests $Z$ and upgrades its complementary product.

(ii) All consumers purchase the rival’s upgraded complementary good at price $\lambda$.

(iii) The rival earns period 2 profits equal to $N(\lambda - c_c) - Z$ while the monopolist’s period-2 profits equal zero.

Lemma 1 tells us that, if the rival’s quality advantage in the complementary product is large and the rival sold complementary units in period 1, then only the rival upgrades and sells complementary units in period 2. The logic here is as follows. If both firms invest $Z$ and upgrade their products, because the rival’s complementary product is superior, the rival sells complementary units in period 2 at $\min[\lambda, (V_R - V_M) + c_c]$. Given $N\lambda > Z + Nc_c$, which means that if $V_R$ is sufficiently high, then the rival invests $Z$
and sells upgraded complementary units in period 2 whether or not it anticipates that the monopolist will upgrade. In turn, as the monopolist knows this, in equilibrium only the rival invests $Z$ and upgrades which means the firm sells its upgraded product at a price of $\lambda$ in period 2.

Lemma 1 considers what happens if consumers in period 1 purchase the monopolist’s primary good and the rival’s complementary good. Another important possibility is that in period 1 consumers purchase the monopolist’s primary and complementary goods sold separately. Analysis of this case yields similar results. That is, if $V_R$ is sufficiently high, then the same basic logic as above yields that in period 2 only the rival invests $Z$ and only the rival sells upgraded complementary units. The only difference here is that in period 2, because consumers at the beginning of the period own the monopolist’s lower quality non-upgraded complementary units rather than the rival’s non-upgraded complementary units, the rival charges $\lambda + (V_R - V_M)$ rather than $\lambda$ for its upgraded complementary units.

The reason these results are important is that they tell us that the logic behind Proposition 1 does not hold when upgrading is possible. In the absence of upgrading, the monopolist could sell individual products and choose prices that guarantee itself profits at least as high as with tying. But this is not true given upgrading. For example, suppose the monopolist sells individual products and the rival sells complementary units in period 1. Then, if $V_R$ and $\lambda$ are both large, the rival sells complementary units in period 2 and earns $N(\lambda - c) - Z$. And there is no way through period-1 pricing that the monopolist can ensure it captures all the period-2 profits associated with upgrading. On the other hand, if the monopolist ties, then it sells upgrades in period 2 and its period-2 profitability is $N(\lambda - c) - Z$. The result is that, if $N(\lambda - c) - Z$ is sufficiently large, that is, larger than the loss in period-1 profits due to tying, the monopolist earns higher profits by tying than by selling individual products. We capture this argument formally in Proposition 2.

**Proposition 2.** Suppose firms sell as opposed to lease their products. Holding all other parameters fixed, if $V_R - V_M > Z/N$ and the added benefit of consuming an upgraded product, $\lambda$, is sufficiently large, then there is a unique equilibrium characterised by (i) to (iv).11

(i) The monopolist sells a tied product to all consumers in period 1.
(ii) The monopolist invests $Z$ at the beginning of period 2 and sells an upgraded complementary product to all consumers in period 2 at a price of $\lambda$.
(iii) The rival does not sell complementary units in either period and does not invest $Z$ in period 2.
(iv) Social welfare is lower than social welfare when the monopolist is not allowed to tie.

An interesting aspect of Proposition 2 is that, when $\lambda$ 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 rival from selling upgraded complementary units in period 2. In response to a

11 Without assuming $V_R - V_M > Z/N$ we are not assured of a unique equilibrium. If $\lambda$ is large but $V_R - V_M < Z/N$, then there is always an equilibrium characterised by (i) to (iv) but it need not be unique. Also, the precise condition for $\lambda$ is that $\lambda > 2(V_R - V_M) + 2c + (Z/N)$.

period-1 price of zero for the monopolist’s complementary good, the rival can choose not to sell complementary units in period 1 but invest and sell upgraded complementary units in period 2. This allows the rival to capture the upgrade value, which is very costly to the monopolist if \( \lambda \) is high. Hence, when a zero price for the complementary good by the monopolist does not stop the rival from selling period-2 complementary units, the monopolist may find that it maximises profits by tying.

Key assumptions in this analysis are that research and development is costly, i.e., \( Z > 0 \), and the monopolist cannot commit in period 1 to its period-2 research and development expenditure.\(^{12}\) If either condition were relaxed, there would be no reason for the monopolist to tie. For example, with \( Z = 0 \) the monopolist’s period-2 complementary product is automatically upgraded, so the rival’s period-2 profit would only reflect the superiority of its product rather than the upgrade value. We believe these two assumptions are quite realistic. Research and development is typically quite costly, so assuming \( Z \) is positive seems innocuous. Further, the research and development process is often quite complex which can make it difficult to commit to the size of future R&D expenditures.\(^ {13}\)

Other important assumptions are that consumers are identical and there is limited product differentiation. If consumers were heterogeneous and there was product differentiation concerning the complementary goods such that some consumers preferred the rival’s complementary good and some preferred the monopolist’s, then results could be quite different. That is, if introducing these changes resulted in the monopolist always investing in research and development even in the absence of tying, then there would be no role for tying. As discussed above, in our analysis tying is a way for the monopolist to avoid problems that arise because it cannot commit to its period-2 R&D expenditure, so there is no role for tying if the monopolist always invests to sell upgraded complementary units to consumers who prefer the monopolist’s complementary product.

Another interesting aspect of Proposition 2 is that, as captured in \((iv)\) of the Proposition, tying reduces welfare. The logic is straightforward. As discussed, when the monopolist ties, all consumers purchase primary and complementary units from the monopolist in period 1 and then upgraded complementary units from the monopolist in period 2. Suppose instead the monopolist was not able to tie because of government regulation. Then in period 2 (and possibly period 1) all consumers would purchase complementary units from the rival rather than from the monopolist. As the monopolist’s complementary product is inferior to the rival’s while the costs of producing the complementary goods are the same, tying reduces social welfare.

\(^{12}\) To be precise, what is important is that the monopolist has a positive value for \( Z \). That is, if we allowed the monopolist and the rival to have different values for \( Z \), what is key for the possibility of a tying equilibrium is that the monopolist’s value for \( Z \) is strictly positive.

\(^{13}\) Given our assumption that prices are non-negative, allowing the monopolist to commit to a period-2 price for the complementary good, without specifying whether or not the good is upgraded, but not a period-2 research and development expenditure would not eliminate the incentive for the monopolist to tie. The reason is that, if \( \lambda \) is sufficiently large, the monopolist cannot reduce the rival’s profit to zero just by committing to a zero price for the period-2 complementary good. However, if the monopolist could commit to a period-2 price specifically for an upgraded complementary unit, then there would be no reason for the monopolist to tie since being able to commit to a period-2 price for an upgraded complementary unit is similar to being able to commit to a period-2 R&D expenditure.
1.3. Selling and Leasing

In the previous subsection, we considered what happens when firms only sell their products. We now consider how results change when firms can either sell or lease. The answer is that when leasing is an option the monopolist has no incentive to tie even in the presence of upgrades. That is, when firms can sell or lease there are equilibria in which the monopolist ties but this is not because monopoly profitability is higher with tying. Rather, monopoly profitability in any equilibrium in which the monopolist does not tie is at least as high and sometimes higher than in the tying cases. We formally consider this case in Proposition 3.

**Proposition 3.** Suppose firms can lease as well as sell their products in the presence of upgrades. For every allowable parameterisation there are two equilibria characterised by the monopolist tying (in one it sells its products and in the other it leases) and in each monopoly profitability equals monopoly profitability in the absence of a rival. There are also other equilibria in which the monopolist markets its products individually and in each of these equilibria monopoly profitability is greater than or equal to monopoly profitability in the absence of a rival (where some of these equilibria are such that the inequality is strict).

The logic here is a two-period variant of Whinston’s logic. Suppose that in period 1 the monopolist leases its products individually, charges marginal cost for its complementary good, and sets the primary-good price equal to the optimal period-1 price for a leased bundle consisting of its primary and complementary goods minus the complementary-good price. This period-1 strategy ensures period-1 profits at least as high as period-1 profits associated with leasing and tying. Now suppose that in period 2 the monopolist upgrades its complementary good and then employs the same pricing strategy, that is, the upgraded complementary good is priced at marginal cost and the price of the primary good is set equal to the optimal period-2 price for a leased bundle minus the price of the upgraded complementary good. This ensures period-2 profits at least as high as period-2 profits associated with leasing and tying. As 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 equally well by leasing and marketing its products individually.

One way to understand the details of Proposition 3 is that leasing is similar to tying in the sense it allows the monopolist to capture period-2 upgrade profits but can also be superior to tying because in a leasing equilibrium it is possible that the monopolist captures a positive share of the surplus associated with the rival’s superior complementary product. To see this, consider a parameterisation in which the added benefit of consuming an upgraded product, \( \lambda \), is sufficiently large that, consistent with Proposition 2, the monopolist would tie if it was restricted to selling its products. For such a parameterisation, 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. In these equilibria, the monopolist captures period-2 upgrade profits but the resolution of the period-2 multiple equilibria problem is such that the monopolist does not capture any share of the surplus associated with the rival’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 captures the period-2 profit associated with upgrading and the resolution of the period-2 multiple equilibria problem is such that the monopolist also captures a positive share of the surplus associated with the rival’s superior complementary good.\textsuperscript{14,15}

What does Proposition 3 imply about social welfare when firms can lease as well as sell their products? Let $W^*$ be social welfare in the absence of a rival and $W$ be social welfare in equilibrium. In each tying equilibrium, $W = W^*$ since tying means that the rival is not able to sell or lease its complementary product. Further, in an equilibrium in which the monopolist markets its products individually and monopoly profitability exceeds monopoly profitability in the absence of a rival, then $W > W^*$ (if monopoly profitability is greater than or equal to monopoly profitability in the absence of a rival, then $W \geq W^*$). The logic here is that, in the absence of a rival, the monopolist extracts all the surplus, or, equivalently, both consumers and the rival receive zero surplus. So, when monopoly profitability in equilibrium exceeds monopoly profitability in the absence of a rival, the monopolist is better off while consumers and the rival are no worse off, so social welfare must be higher.

As a final point concerning the analysis of this Section, although we have shown the results using a specific model characterised by durable goods and upgrades, the basic argument is more general. Consider any setting characterised by a monopolist which sells or leases a primary good at some early date and a non-monopolised complementary good that is developed and marketed later. The general point is that, if in such a setting the monopolist cannot commit at the initial date to its later actions, then tying or similar behaviour can be profitable if the monopolist is restricted to selling its output but not when leasing is feasible. Further, there are various settings in addition to durable goods and upgrades in which this scenario can arise. For example, consider a two-period setting in which in the first period primary and complementary goods are available just as in our model, while in the second period there are no upgrades but both the monopolist and a rival can invest in the development of a new complementary product. Then similar to what is true in our analysis, if the monopolist is restricted to selling its products, then it will sometimes want to design its primary product so that any new complementary product developed by the rival is incompatible. However, if leasing is possible, then the monopolist cannot increase its profits through such behaviour. Another example along these lines occurs when there is a single complementary good that is not durable and there is a fixed cost of production in each period associated with producing the complementary product, where the monopolist must choose whether or not to incur this fixed cost before prices and purchase decisions are determined.

\textsuperscript{14} Consistent with this discussion, one way to view the role of leasing in this analysis is that, relative to the outcome when the monopolist sells its products, it is a way for the monopolist to reduce the rents the rival can capture. The leasing argument here is thus related to papers such as Aghion and Bolton (1987) and Farrell and Katz (2000) where various practices are used as ways of reducing rival profitability.

\textsuperscript{15} In the next Section, we impose a surplus sharing rule to avoid multiple equilibria and, in particular, assume that when the monopolist does not tie period-2 prices are such that the rival receives $\rho$ of the period-2 surplus associated with the rival’s superior complementary product and the monopolist receives $(1 - \rho)$ of this surplus. If we imposed this surplus sharing rule here and assumed $\rho < 1$, then leasing without tying would necessarily be preferred by the monopolist to tying.
In summary, in this Section we have shown that a primary-good monopolist sometimes ties 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 because it is unable to commit credibly to future actions as would occur if complete contingent claims contracts were available. Hence, if the upgrade is sufficiently valuable, then the monopolist may tie to capture those upgrade profits. The analysis also provides a new reason for why such a firm might lease but not tie as leasing is an alternative way for the firm to capture upgrade profits. In fact, in some cases leasing without tying will be preferred because it allows the firm to capture both upgrade profits and some of the profits due to the rival’s superior complementary product.

2. Tying in the Presence of Upgrades and Switching Costs

This Section considers 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. The reason is that, if consumer switching costs are substantial and individuals consume the rival’s complementary product in period 1, then in period 2 the monopolist’s upgraded complementary good becomes a less attractive substitute for the rival’s upgraded product. The result is that the monopolist has limited ability to capture period-2 profits due to switching costs through leasing. Note that this result may help to explain IBM’s behaviour in the 1960s mentioned earlier. Specifically, during the 1960s IBM leased its mainframe computers and tied or bundled the computers with software and services. The previous analysis does not explain this behaviour because in that analysis there is no return to tying if the firm leases. But in the analysis in this Section where switching costs are introduced there can be a return to tying even when the monopolist leases.16

One reason that there can be switching costs in real-world markets is that the complementary product is associated with learning-by-doing. For example, digital media players such as Windows Media Player and RealPlayer have basic capabilities such as playing audio, video and viewing images on a computer, as well as various other capabilities such as giving the user the ability to rip music from and copy music to compact discs, synchronise content with a digital audio player and other mobile devices, and allow users to rent or purchase music from online stores. Learning the steps needed to become an expert at all these functions can take a significant investment in time. In the typical case, a producer’s initial and upgraded products will work in a more similar fashion than will the producer’s initial product and a rival’s upgraded product. So, for example, there would be switching costs in moving from Windows Media Player 11 to RealPlayer 14 rather than from Windows Media Player 11 to Windows Media Player 12 because of the extra time a consumer currently using Windows Media Player 11 would require to become an expert on RealPlayer 14.

16 In the analysis in this Section, leasing and tying yield the same profits as selling and tying, so the analysis does not fully explain IBM’s behaviour. But if we introduced some additional element that yields a return to leasing such as time inconsistency (Coase, 1972; Bulow, 1982), then we would have an explanation for why a firm might both tie and lease.
2.1. The Model

To understand what switching costs mean for our model, suppose each firm upgrades in period 2. Then, an individual who consumes the monopolist’s complementary good in period 1 will have a higher valuation for the monopolist’s upgrade in period 2 than will an individual who consumed the rival’s complementary good in period 1 (an analogous statement holds for an individual who consumed the rival’s complementary product in period 1).

To be precise, the gross benefits that consumers receive in period 2 from various consumption combinations are now as follows.\(^{17}\) Consider first an individual who consumed a system containing the monopolist’s complementary good in period 1. If in period 2 the individual consumes a system that contains the monopolist’s complementary product, then he receives \(V_M + \Delta\) if it is not upgraded and \(V_M + \Delta + \lambda\) if it is, where \(\Delta > 0\). On the other hand, if in period 2 the individual consumes a system that contains the rival’s complementary product, then he receives \(V_R\) if it is not upgraded and \(V_R + \lambda\) if it is. In this specification, \(\Delta\) captures the switching costs, that is, the consumer receives an added benefit if he consumes the same brand of the complementary product in period 2 as in period 1, while as before \(\lambda\) is the added benefit of consuming an upgraded product.

Now consider an individual who consumed a system containing the rival’s complementary good in period 1. This case is symmetric to the one above. If in period 2 the individual consumes a system that contains the rival’s complementary product, then he receives \(V_R + \Delta\) if it is not upgraded and \(V_R + \Delta + \lambda\) if it is. On the other hand, if in period 2 the individual consumes a system that contains the monopolist’s complementary product, then he receives \(V_M\) if it is not upgraded and \(V_M + \lambda\) if it is.

If in period 1, a consumer owns a system containing both the monopolist’s and the rival’s complementary goods, then the consumer must choose which complementary good to use and in period 2 he only receives \(\Delta\) if he uses a complementary good produced by the same firm. So, given our assumption that prices cannot be strictly negative and our earlier assumption that the marginal cost for producing the complementary product is strictly positive, in equilibrium in period 1 consumers never purchase or lease complementary goods from both producers.

We also introduce an additional assumption concerning 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. For example, suppose both firms lease, all consumers in period 1 lease the rival’s complementary product and both firms upgrade at the beginning of period 2. Given this, consider pricing in period 2.\(^{18}\) One equilibrium set of period-2 prices is that the monopolist charges \(V_M + \lambda - c_c\) for its

\(^{17}\) We assume that switching costs take the form of learning-by-doing as discussed above. This means that an individual who consumes a complementary unit produced by firm \(j\) in period 1 receives an extra benefit if the individual consumes a complementary unit in period 2 produced by firm \(j\), but no extra benefit in period 2 if the individual consumes a complementary unit produced by a different firm. Similar results would be found if we instead assumed a different specification for switching costs not consistent with learning-by-doing where an individual who consumes a complementary unit produced by firm \(j\) in period 1 receives no extra benefit if the individual consumes a complementary unit in period 2 produced by firm \(j\), but the individual bears a cost in period 2 if the individual consumes a complementary unit produced by a different firm.

\(^{18}\) In terms of period-2, prices which is our focus in terms of avoiding the multiplicity of prices, the problem only arises when the monopolist leases.
primary product and the rival charges \((V_R - V_M) + \Delta + \epsilon_c\) for its upgraded complementary product (here and in the following set of equilibrium prices, consumers lease the complementary good from the rival as long as the monopolist charges more than \(\epsilon_c\) for its complementary product). In this equilibrium to the period-2 pricing subgame, the rival receives all of the surplus associated with consumers preferring its version of the upgraded complementary product. However, in another set of equilibrium period-2 prices, the monopolist charges \(V_R + \Delta + \lambda - \epsilon_c\) for its primary product and the rival charges \(\epsilon_c\) for its upgraded complementary product. In this equilibrium to the period-2 pricing subgame, the monopolist receives all of the surplus associated with consumers preferring the rival’s version of the complementary good. In fact, any division across the two sellers is consistent with equilibrium.

Similar to the approach taken in Choi and Stefanadis (2001) and Carlton and Waldman (2002), we assume that when this indeterminacy arises in period 2 the prices that emerge give \(\rho\) of the surplus to the rival and \((1 - \rho)\) to the monopolist, \(\rho > 0\). The restriction \(\rho > 0\) means the rival receives a strictly positive share of the surplus. Note that if this was not true, i.e., \(\rho = 0\), then when it can lease there would be no incentive for the monopolist to tie because leasing by itself would allow the monopolist to capture all of the period-2 value associated with consumer switching costs. We also restrict the analysis to parameterisations in which \(N\rho(\lambda - \epsilon_c) > Z\). This assumption ensures that, if consumers in period 1 lease the monopolist’s primary good and the rival’s complementary good, both firms upgrade in period 2 when the switching cost is high. This assumption reduces the number of cases that need to be considered.\(^{19}\)

2.2. Analysis

If firms only sell their products, then results here are similar to those in Section 2. First, if the rival’s complementary product is sufficiently superior, then in the absence of tying the rival earns period-2 profits that are an increasing function of the added benefit of consuming an upgraded product. Second, because of the limited ability of the monopolist to capture upgrade profits through the period-1 price of the primary good, if this added benefit is sufficiently large, then the monopolist ties and directly captures upgrade profits. Third, because tying forecloses a superior complementary product, for these parameterisations tying reduces social welfare.

We now consider what happens when firms can either sell or lease. We begin with a preliminary result concerning what happens in period 2 when in period 1 all consumers lease primary units from the monopolist and complementary units from the rival. Note that in the analysis of period 2 there is a potential multiple equilibria problem concerning the R&D decision. Similar to our analysis in Lemma 1 concerning what happens when firms are restricted to selling, we restrict the analysis in Lemma 2 to

\(^{19}\) An alternative specification that yields the same results is that in period 2 prices are chosen sequentially rather than simultaneously but there is \emph{ex ante} uncertainty concerning whether the monopolist or the rival moves first. In this alternative specification, \(\rho\) represents the probability the rival moves first. Also, the restriction that \(N\rho(\lambda - \epsilon_c) > Z\) is more of a constraint the smaller is \(\rho\). But note that if there are many consumers in the market such as is true for example in the Microsoft case, it seems reasonable that this restriction would be satisfied even if \(\rho\) were small.
parameterisations in which the rival’s complementary product is sufficiently superior in period 2 such that this multiple equilibria problem does not arise.

**Lemma 2.** Suppose all consumers in period 1 lease the monopolist’s primary good and the rival’s complementary good. Holding all other parameters fixed, if the switching cost, $\Delta$, is sufficiently large, then (i) to (iv) characterise behaviour in period 2.\(^{20}\)

(i) Both firms invest $Z$ and upgrade.

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

(iii) The price for the monopolist’s primary product is $V_M + \lambda - c_e + (1 - \rho) (V_R - V_M + \Delta)$, while the price for the rival’s complementary product is $c_c + \rho (V_R - V_M + \Delta)$.

(iv) The monopolist’s period-2 profit equals $N \left[ V_M + \lambda - c_e + (1 - \rho) (V_R - V_M + \Delta) \right] - Z$, while the rival’s period-2 profit equals $N \rho (V_R - V_M + \Delta) - Z$.

Lemma 2 tells us what happens in period 2 when in period 1 consumers lease primary units from the monopolist and complementary units from the rival. In particular, if the switching cost is sufficiently large, then the following three conditions are satisfied. First, there is a unique equilibrium in which both firms upgrade and consumers lease primary units from the monopolist and upgraded complementary units from the rival. The return here for the monopolist to upgrade even though it does not sell upgraded complementary units in period 2 is that upgrading allows the monopolist to raise the lease price for the primary product and in this way capture all of $\lambda$. Second, as just stated, the monopolist captures all of the profits due to the improved upgrade quality. Third, even though the monopolist upgrades, its period-2 profit is such that the monopolist captures only $(1 - \rho)$ of the period-2 profit due to the switching cost while $\rho$ of this profit is captured by the rival.

It is the second and third results that are our focus. The second result is an example of the main point of the leasing discussion of the previous Section. That is, when the monopolist leases in period 1, it always has the option in period 2 of upgrading its complementary product and in this way capturing period-2 profits due to the increased upgrade quality. In other words, if the monopolist has the option of leasing, then from the standpoint of profits due to the upgrade value the monopolist does at least as well leasing individual products as it does by tying.

In contrast, the third result tells us that in terms of period-2 behaviour 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 period-2 profits due to the upgrade value by leasing and upgrading in period 2. In contrast, even when the monopolist upgrades, Lemma 2, (iii) and (iv) tell us that if in period 1 consumers lease the monopolist’s primary good and the rival’s complementary good, then period-2 prices are such that the monopolist only captures $(1 - \rho)$ of the period-2 profits due to the switching costs. Note, however, that if the monopolist ties (whether or not it leases or sells), the monopolist captures all of the period-2 profits due to the switching costs. The result is that, if switching costs are sufficiently large, then the monopolist can have an incentive to tie. This logic is captured formally in Proposition 4.

\(^{20}\) The precise condition for $\Delta$ is that $\Delta > \left( \frac{Z}{N\rho} \right) + V_M - V_R$. 

Proposition 4. Suppose firms can either sell or lease. Holding all other parameters fixed, if the added benefit of consuming an upgraded product, \(k\), and the switching cost, \(D\), are both sufficiently large, then (i) to (iv) characterise equilibrium behaviour.

(i) The monopolist either sells or leases a tied product to all consumers in period 1 (given the firm ties, selling and leasing yield the same value for monopoly profits).

(ii) The monopolist invests \(Z\) at the beginning of period 2.

(iii) If the monopolist sold (leased) a tied product in period 1, then it sells an upgraded complementary good to all consumers in period 2 (leases a tied good consisting of a primary unit and an upgraded complementary unit to all consumers in period 2).

(iv) The rival does not sell or lease complementary units in either period and does not invest \(Z\) in period 2.

(v) If \(2N(V_R - V_M) > Z\), then social welfare in equilibrium is lower than social welfare when the monopolist is not allowed to tie.

Proposition 4 shows that, given switching costs, tying can be optimal even when leasing is possible. To see the logic here, suppose the monopolist leases, does not tie, and upgrades in period 2. If consumers lease the rival’s complementary product in period 1 and the rival’s upgraded complementary product in period 2, our surplus sharing assumption means the monopolist’s period-2 profit equals \(N(V_M + \lambda - c_e) - Z + N(1 - \rho)(V_R - V_M + \Delta)\). In contrast, by tying, leasing, and upgrading, the monopolist receives period-2 profit equal to \(N(V_M + \lambda + \Delta - c_e) - Z\). That is, tying allows the monopolist to capture all of the period-2 value due to the switching costs but none of the value due to the rival’s superior complementary product, while not tying and having individuals in period 1 consume the rival’s complementary product means that in period 2 the monopolist captures \((1 - \rho)\) of the value due to both switching costs and the rival’s superior complementary product. If \(\Delta\) is sufficiently large, the tying outcome is preferred.\(^{21}\)

One interesting aspect of Proposition 4 is that both the added benefit of consuming an upgraded product, \(\lambda\), and the switching cost, \(\Delta\), have to be large to ensure tying is employed. From the above discussion, one might think that only \(\Delta\) needs to be large to ensure this. But the above discussion assumes that, if the monopolist does not tie, its alternative is to lease. But this is not necessarily the case. It is possible that the best alternative is selling. Further, if the monopolist’s best alternative is selling, then it is possible that it can capture much of the value of the period-2 switching costs through the period-1 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 \(\lambda\) is sufficiently large. Hence, if \(\lambda\) and \(\Delta\) are both sufficiently large, then the monopolist ties.

Another interesting aspect of Proposition 4 is that tying used to monopolise the complementary market does not always hurt social welfare. If in the absence of tying the monopolist sells its products, then as in Proposition 2 tying hurts social welfare.

\(^{21}\) A key assumption for this result to hold is that firms are not allowed to charge strictly negative prices for their products. If firms were completely unconstrained in their ability to charge negative prices, then tying could not be used by the monopolist to increase its profitability. The reason is that in the leasing case, when switching costs are large, competition between the firms in period 1 would result in negative prices for the complementary product which, in turn, allows the monopolist to capture the switching-cost value through the period-1 price of the primary product. In Section 3, we discuss this point in more detail.

However, if in the absence of tying the monopolist leases, then tying can improve social welfare. The logic is as follows. For some parameterisations, if the monopolist cannot tie, then it leases, both firms upgrade, and individuals in period 2 consume the monopolist’s primary product and the rival’s complementary product. For these parameterisations, tying has two effects on social welfare. There is a social welfare cost equal to $2N(V_R - V_M)$ because individuals consume the monopolist’s lower quality complementary product, but there is also a social-welfare benefit equal to $Z$ because only the monopolist invests. In these parameterisations, social welfare increases with tying if $2N(V_R - V_M) < Z$. However, if $2N(V_R - V_M) > Z$, then tying decreases social welfare. So, if $2N(V_R - V_M) > Z$, then, as stated in Proposition 3, tying necessarily decreases social welfare.\(^{22}\)

There are a number of simplifying assumptions in the analysis here and in the previous Section (some of which are relaxed in the next Section) such as that consumers are homogeneous and the rival’s complementary good is always superior both in terms of the period-1 basic version and the period-2 upgraded version. But most of these assumptions are made to make the argument easy to follow rather than because the assumptions are essential. The main idea that in the presence of upgrades tying can be used for leveraging a monopoly position even when the primary good is essential is robust to various ways of complicating the analysis. In Section 3, we discuss three such variants of our analysis that we feel are of particular interest.

One assumption, however, is worth emphasising. As we briefly alluded to in the previous Section, a key assumption of our analysis here and in the previous Section is that in period 1 the monopolist and the rival cannot write long-term contingent contracts either with each other or with consumers that bind themselves to specific actions in period 2. If they could, then the monopolist would have no incentive to tie because there would always be a long-term contract consistent with individuals consuming the rival’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 rival’s superior complementary product and only the rival would invest $Z$. This is just the Coase theorem. Despite the positives associated with such contracting, however, in real-world situations such contracts are frequently difficult or infeasible because of both the difficulty of monitoring and enforcing contractual commitments concerning research and development and prices and legal impediments due to the antitrust laws.

An interesting question along these lines is whether in the type of framework we look at the monopolist would ever tie if this type of efficient contracting were available. For example, in the mid 1990s Microsoft signed a licence agreement with RealNetworks (then known as Progressive Networks) and then tied or bundled RealPlayer with Internet Explorer. If we think of RealPlayer as the rival’s superior complementary product in our

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\(^{22}\) This result importantly depends on our timing assumption that R&D choices occur prior to prices being determined, that is, if R&D levels were chosen after prices there would never be duplication of R&D investments even in the absence of tying. However, given that prices can usually be quickly changed while there is typically a lag between the time an R&D choice is made and the new product is ready for sale, assuming that R&D choices are made prior to prices being determined seems quite reasonable. Note further, if we allowed the monopolist and rival to have different values for $Z$, then whether social welfare rises or falls with tying depends on the relationship between $2N(V_R - V_M)$ and the rival’s value for $Z$. 

models, our models do not explain why Microsoft would tie the products. But possibly an extension of our second model could explain the behaviour. For example, suppose there was a second rival complementary producer, product differentiation concerning the complementary goods, and heterogeneous consumers. We conjecture that using this Section’s switching cost framework, if consumers vary in terms of which complementary product they prefer, it could be in the best interest of the monopolist to tie even when it licenses a rival’s complementary product which is preferred by most consumers.23

In summary, in the presence of consumer switching costs, even when the monopolist can lease, the monopolist can have an incentive to tie. The reason is that switching costs mean that if individuals consume the rival’s complementary product in period 1, then in period 2 the monopolist’s complementary product is perceived as lower quality and thus a worse substitute for the rival’s complementary product. As a result, with switching costs the only way the monopolist can capture all of the profits associated with the switching costs in period 2 is to have individuals consume the monopolist’s complementary product in period 1. Only a tie ensures this. We also showed that tying in this case frequently decreases 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 parameterisations it reduces the aggregate expenditure on R&D.

3. Extensions

Sections 1 and 2 showed that the introduction of upgrades and switching costs can result in tying by a primary-good monopolist even when the monopolist’s primary good is essential. This Section discusses three extensions: reversible ties; negative prices; and primary-product upgrades.

3.1. Extension 1: Reversible Ties

Following Whinston (1990), previously we assumed ties were irreversible, that is, when the monopolist tied consumers could not add the rival’s complementary product to the monopolist’s tied product. At least for the case of Microsoft this assumption is not correct as consumers frequently add a rival’s complementary product to Windows even when Microsoft has tied a similar product to Windows. This discussion considers what happens to our analysis when ties are reversible.

Suppose ties are completely reversible, that is, there is no added cost associated with consumers adding the rival’s complementary product to a system consisting of the

23 In our first model which has no switching costs, there is a role for tying when the monopolist cannot commit to investing in R&D in period 2. So in that framework, if there is product differentiation and consumers vary in terms of which complementary product they prefer, then as discussed earlier there is no role for tying if in the absence of tying the monopolist invests in R&D in period 2 to sell upgraded units to the consumers who prefer the monopolist’s complementary product. In contrast, in the switching-cost framework of this Section, tying also serves to force consumers to buy the monopolist’s complementary product in period 1. So in the switching-cost framework, if there is product differentiation and consumers who vary in terms of which complementary product they prefer, there should be a role for tying even when in the absence of tying the monopolist invests in R&D in period 2 to sell upgraded units to the consumers who prefer the monopolist’s complementary product.

monopolist’s tied products. In this case, tying is never the unique equilibrium outcome. The reason is that under costless reversibility tying is basically equivalent to having the monopolist set the complementary-good price at zero. Hence, if there is an equilibrium in which the monopolist ties to stop consumers from purchasing or leasing the rival’s complementary products, there is also an equilibrium in which the monopolist markets its product individually and sets the complementary-good price at zero.

Another possibility is that ties are what might be called partially reversible, that is, a consumer can add the rival’s complementary product to a system consisting of the monopolist’s tied products but there is an added cost of doing so. This added cost can take the form of an added cost faced by the consumer, an increase in the rival’s cost structure or a lowering of the functionality of the rival’s complementary product. For any of these cases, there will be some situations in which the monopolist ties to stop consumers from purchasing or leasing the rival’s complementary product.

To see the logic here, consider Section 2’s analysis. For some parameterisations, the monopolist wants to prohibit the rival from selling or leasing its complementary good and the monopolist can achieve this by setting the period-1 price for its complementary good at zero. However, for other parameterisations a strictly negative period-1 price is needed to foreclose the rival. For these parameterisations, if ties are reversible but increase a consumer’s cost of adding the rival’s product to a system consisting of the monopolist’s tied product, then tying may be optimal if this cost is sufficiently large.

The reason is that tying is equivalent to setting a negative period-1 price for the complementary good equal to the added cost. In turn, as a sufficiently low negative price makes it unprofitable for the rival to sell or lease, the monopolist may tie if this cost is sufficiently large. Note that this argument 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.

What is interesting about this discussion is that it is consistent with allegations concerning Microsoft’s behaviour. When Microsoft ties it has the option of a contractual tie in which Windows and the application program are distinct products sold as a package and a physical tie in which the application code is physically integrated into the Windows programming code. In many cases, Microsoft has chosen the latter option rather than the former. The result can be that a rival faces higher costs in developing its complementary products and/or a reduction in the functionality of the product. In addition, Microsoft frequently tries to keep its software interfaces secret which can directly serve to increase rivals’ costs and/or lower the functionality of rivals’ products.24

The discussion in this Section provides one explanation for how such behaviour can be in Microsoft’s interests.

24 By software interface here we are referring to code through which programs, for example, an operating system and an application, communicate with each other. When Microsoft physically integrates the application code into the Windows programming code the result can be the same as keeping the software interfaces secret. That is, such integration can make it more difficult or maybe even impossible for a rival to reverse engineer Microsoft’s applications program and have its own product communicate with Windows in the same way that Microsoft’s program does. It is in this way that the physical integration of an applications program into Windows programming code can increase rivals’ costs and/or reduce the functionality of rivals’ products. See Gilbert and Katz (2001) and Whinston (2001) for detailed discussions of Microsoft’s behaviour.

3.2. Extension 2: Negative Prices

Throughout our analysis, we impose the constraint that prices are non-negative. This assumption is not essential for our analysis in Section 1 characterised by upgrades only. The reason is that by selling individual products and setting a negative price for the complementary product in period 1 the monopolist cannot stop the rival from upgrading in period 2 and capturing period-2 profits due to the upgrade value.\(^\text{25}\)

In contrast, the non-negative price assumption is important for the analysis of Section 2. An important aspect of our argument in that Section is that when it leases the monopolist has limited ability to capture period-2 consumer value associated with switching costs through period-1 prices and period-1 competition for the lease of complementary units. Such competition is limited because we assume that prices – in particular, period-1 prices for the complementary good – cannot be negative (or contingent on period-2 actions). Here, we discuss how that analysis changes 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 \(P^1_c, \quad P^1_c < 0\). This change basically has no effect on the qualitative nature of the results. That is, it would still be the case that (i) to (v) of Proposition 4 would hold given the added benefit of consuming an upgraded product, \(\lambda\), and the switching cost, \(\Delta\), are both sufficiently large. The only change is that for any parameterisation the minimum \(\Delta\) required for tying to be optimal would be higher.

A second way to relax the non-negative price constraint is to assume that firms can set any price no matter how negative but cannot monitor and ration how many units a consumer leases or purchases. Relaxing the assumption in this way has no effect on our results. The reason is that, although strictly negative prices would be part of the choice set, no firm would ever choose a strictly negative price. This is because, if a firm charged a strictly negative price, consumers would maximise 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. Also, a possibly more realistic related assumption is that firms can set negative prices while monitoring and rationing are feasible but costly, where this cost is increasing in the incentive for consumers to purchase the negatively priced good. In this case, because of the monitoring costs, the firm would again find that for \(\lambda\) and \(\Delta\) sufficiently large the firm could not duplicate the profitability of the tying equilibrium by charging a negative price.

A third way of relaxing the non-negative price constraint is to assume that the monopolist and the rival can both 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 period 1 would be offered a strictly negative period-1 price for the complementary unit. If we assume that in addition to the \(N\) identical consumers that we assume in our basic analyses there are a large number of consumers who place no value on the primary and

\(^{25}\) We show this formally in Carlton and Waldman (2009) which allows negative prices and imposes Trembling-Hand Perfection to rule out an unrealistic equilibrium characterised by non-credible threats.
complementary products, 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 period-1 primary and complementary-good prices be non-negative. As a result, for sufficiently large $\lambda$ and $\Delta$ the monopolist would still tie.

In summary, one can relax the non-negative price constraint in a variety of ways without changing the qualitative nature of the results in Section 2. However, if there is no constraint on the magnitude of the negative price that can be charged, the monopolist can price discriminate and costlessly monitor in the sense that only consumers who purchase or lease a primary unit in period 1 would be offered a strictly negative period-1 price for the complementary good and there are no consumers other than the $N$ identical consumers assumed initially, then tying cannot be used to increase profits. In that case, even when switching costs are very high, the monopolist can capture all the switching cost value by leasing, charging a negative period-1 price for its complementary good, and a high price for the primary good that includes the switching-cost value. The fact that pricing of this sort is rare (we are unaware of any empirical examples of such cases) serves to confirm the reasonableness of our approach.

3.3. Extension 3: Primary-Product Upgrades

In Sections 1 and 2, 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 behaviour concerning Windows and IBM’s behaviour in an earlier era were characterised 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 1 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 period 2 does not change the basic conclusion, that is, 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 leasing 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 period-2 complementary-good upgrade profits by upgrading and optimally setting the period-2 prices for its primary and complementary goods. But this is incorrect. Because in period 2 consumers own the monopolist’s old primary good, consumers have the option of purchasing the rival’s upgraded complementary good and nothing else. As a result, the monopolist has limited ability to capture period-2 complementary-good-upgrade profits by appropriately pricing individual products which means that for some parameterisations tying will still be optimal. Note that one interpretation of the result in this case is that, because of sales of the primary good in period 1, the upgraded primary good in period 2 is not essential. And because it is not
essential, allowing the monopolist to sell upgraded primary units in period 2 does not fully eliminate the monopolist’s incentive to tie.

Now consider the analysis of Section 2 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 rival’s complementary good in period 1, then in period 2 the monopolist’s complementary good is less attractive, which means optimal pricing of period-2 leased units gives the monopolist limited ability to capture period-2 profits 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 period 2. Even with an upgraded primary product, the monopolist would have limited ability to capture period-2 switching-cost profits by leasing individual products and optimally pricing period-2 goods. Hence, the basic finding that the monopolist would have an incentive to tie when switching costs and upgrade valuations are both 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.

4. Conclusion

In a classic paper, Whinston (1990) focused on one-period models and showed that if a monopolist’s primary good is essential for all uses of a complementary good, then with fixed proportions in consumption tying cannot be used to increase profits by leveraging or extending the monopoly to the complementary-good market. Since arguably many important real-world tying cases seem to fall into this category, including some of Microsoft’s tying decisions and also IBM’s in an earlier era, this result potentially has important policy implications about the desirability of tying. Our article shows that the result that a monopolist of an essential primary good will never tie to extend or leverage the monopoly into the tied-good market does not apply when upgrades are important, as is common in many markets including software markets. In such settings, tie-ins are one way – and not necessarily a socially efficient way – for the monopolist to commit to future actions and increase monopoly profits when the firm is otherwise unable to commit to future actions through contingent contracts.

Using two-period models, our analysis shows that the presence of 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 period 1 can help the monopolist to capture period-2 upgrade profits. This occurs because, if the monopolist sells individual products and the rival sells complementary units in period 2, then there are no period-2 sales from which the monopolist can capture period-2 upgrade profits. This analysis also implies a rationale for leasing as an alternative to selling and tying. The second is that, even if firms can lease, if switching costs are also important, then tying may be used to capture period-2 profits associated with the switching costs. The logic here is that, if the monopolist leases individual products and in period 1 individuals consume the rival’s

complementary product, then the monopolist has limited ability to capture period-2 switching-cost profits because the switching costs increase the period-2 difference in the value consumers place on the two complementary products.

In terms of the continuing public-policy debate about Microsoft’s behaviour, this article and our earlier (2009) tying paper show that there are various theoretical arguments that enable one to understand many of Microsoft’s tying decisions as a way for Microsoft to preserve and extend its market power. In our earlier paper, we showed that some of these decisions may be understood as a way Microsoft preserves its market power in Windows. In this article, we show that some of these decisions may be viewed as a way for Microsoft to extend its market power to products complementary to Windows (see the caveats in footnotes 2 and 7 concerning our use of the word ‘extend’). Although theoretical possibility by itself does not prove what Microsoft’s true motivations are, our two papers together throw doubt on the contention that economic theory does not support monopolisation 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-ins because tie-ins frequently have an efficiency justification and courts frequently have difficulty correctly identifying the consequences of tying behaviour. See Carlton and Heyer (2008) and Carlton et al. (2008) for general discussions of our views for optimal antitrust policy for tying behaviour.

A related point concerns what our analysis suggests if tying is allowed in the type of setting we consider. First, whenever a superior complementary producer exists and the monopolist ties to exclude this rival, there is an incentive for the monopolist to achieve internally the same efficiency as its rival. Second, 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 rival could be socially desirable, even though it appears to turn a possible duopoly in the complementary good into a monopoly. Alternatively, without 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 as 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 concerns as a merger, yet like a merger could be efficient.

There are a number of directions in which our analysis can be extended but two stand out. First, we have considered two-period models with a single cohort of consumers who are in the market in both periods. It would be interesting to extend the model to more periods with a flow of new consumers in each period, to see how consumer growth affects the results. Second, in our analysis initial qualities and upgrade qualities are taken as fixed as opposed to being decision variables of the firms. Given the interest in how Microsoft’s tying behaviour affects the pace of innovation in the software industry, an interesting extension would be to incorporate R&D choices that endogenously determine initial and upgrade qualities – see Choi (1996, 2004) for related analyses.
Appendix

Proof of Proposition 1

Below $\pi_M$ denotes monopoly profitability in equilibrium while $\pi_M^*$ denotes monopoly profitability in the absence of a rival. Suppose first that the monopolist ties. Then, the rival is not able to sell its complementary product. Because consumers are identical and $\lambda = 0$, in this case equilibrium behaviour is that the monopolist charges $2V_M$ for the tied product in period 1, neither firm invests, and consumers purchase the tied product in period 1. This yields monopoly profits the same as if there were no rival, i.e., $\pi_M = \pi_M^* = N(2V_M - \epsilon_p - \epsilon_c)$.

Now suppose the monopolist does not tie. One equilibrium to the resulting subgame is that the monopolist charges $V_M - \epsilon_c$ for the primary product, $\epsilon_c + \epsilon$ for its complementary product, the rival charges $(V_R - V_M) + \epsilon_c$ for its complementary product, and consumers in period 1 purchase primary units from the monopolist and complementary units from the rival (this is equilibrium behaviour 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 as 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. As the monopolist had the option of tying and earning $\pi_M^*$, 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 $V_R - \epsilon_c$ for the primary product, $\epsilon_c$ for its complementary product, the rival charges $\epsilon_c$ for its complementary product, and consumers in period 1 purchase primary units from the monopolist and complementary units from the rival (this again is equilibrium behaviour as each firm’s pricing strategy is a best response to the other firm’s pricing strategy). This yields $\pi_M = \pi_M^* + N(V_R - V_M)$. Notice that since it is possible this is the subgame equilibrium if the monopolist does not tie, one equilibrium to the full game is characterised by the monopolist not tying and $\pi_M \geq \pi_M^*$. 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 rival does not invest. Then, its period-2 profit equals zero. Suppose only the rival invests. Then, the rival charges a period-2 price for its upgraded complementary good equal to $\lambda$, earns period-2 profit equal to $N(\lambda - \epsilon_c) - Z$, and the monopolist earns period-2 profit equal to zero. Suppose both firms invest. Bertrand competition means that the monopolist charges $\epsilon_c$ for its upgraded complementary good, the rival charges $\lambda$ for its upgraded complementary good, and consumers purchase the rival’s upgraded complementary good. The rival earns period-2 profit equal to $N(\lambda - \epsilon_c) - Z[\alpha V_M + \lambda - V_R] = (\lambda)\epsilon_c$ and the monopolist earns period-2 profit equal to $N(\lambda - \epsilon_c) - Z$ (note that in this step of the argument we are implicitly imposing a Trembling-Hand type assumption that stops the monopolist from charging less than $\epsilon_c$ for its upgraded complementary good). Suppose $V_R > V_M + (Z/N)$. Then, the above yields the rival must invest. But if the monopolist anticipates the rival will invest, then the monopolist will not and (i), (ii) and (iii) hold.

Proof of Proposition 2

Suppose the monopolist ties. Then, the rival cannot sell complementary units in either period and so it does not invest at the beginning of period 2. This means the monopolist sells new tied units at the beginning of period 1 at a price equal to $2V_M$, it invests $Z$ in period 2 and then sells upgraded complementary units at a price $\lambda$, and its overall profit equals $N(2V_M + \lambda - \epsilon_p - 2\epsilon_c) - Z$.

Now suppose the monopolist does not tie and let \( V^*_R = V_M + (Z/N) \). Given \( V_R > V^*_R \), we know that if consumers purchase primary units from the monopolist and complementary units from the rival in period 1, then (\( \text{i} \)) to (\( \text{iii} \)) of Lemma 1 hold. Given the constraint that prices must be non-negative we have that the monopolist’s period-1 price for its primary product cannot exceed \( 2V_R \), but this means its overall profit must be less than or equal to \( N(2V_M - \epsilon_p) \). But comparing this expression with the profit expression given tying yields that, if \( \lambda \) is sufficiently large and \( V_R > V^*_R \), then the monopolist will tie if it anticipates that in period 1 consumers will purchase primary units from the monopolist and complementary units from the rival.

Now suppose the monopolist does not tie and consumers purchase primary and complementary units from the monopolist in period 1. Employing a logic similar to the one employed in the proof of Lemma 1, in this case if \( \lambda \) is sufficiently large and \( V_R > V^*_R \), then only the rival invests in period 2 and additionally the rival sells upgraded complementary units to all consumers at the price \( \lambda + (V_R - V_M) \). Given the individual rationality constraint on the part of consumers, this means monopoly profitability cannot exceed \( N(2V_M - \epsilon_p - \epsilon_c) \). But comparing this expression with the profit expression given tying yields that, if \( \lambda \) is sufficiently large and \( V_R > V^*_R \), then the monopolist will tie if it anticipates that in period 1 consumers will purchase primary and complementary units from the monopolist.

Now consider period 1. If the monopolist does not sell primary units in period 1, 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 period 1 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. Combining this with results above, we now have that if \( \lambda \) is sufficiently large and \( V_R > V^*_R \), then the monopolist ties and (\( \text{i} \)) to (\( \text{iii} \)) hold.

Finally, one can show that, if the monopolist is not allowed to tie, in any equilibrium consumers must consume a system in each period. Further, using arguments above, if \( \lambda \) is sufficiently large and \( V_R > V^*_R \), in any such equilibrium in period 2 only the rival invests and the rival sells upgraded units to all consumers. Hence, if \( \lambda \) is sufficiently large and \( V_R > V^*_R \), 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 rival’s higher quality complementary product at least in period 2 when it is not allowed to tie. Below let \( W \) denote social welfare in equilibrium and \( W^N \) social welfare when the monopolist is not allowed to tie. We now have that, if \( \lambda \) is sufficiently large and \( V_R > V^*_R \), then \( W < W^N \).

\textbf{Proof of Proposition 3}

Suppose first that the monopolist ties and sells its products. Then the rival is not able to sell or lease its complementary product. Because consumers are identical and \( N\lambda > Z + N\epsilon_c \), in this case equilibrium behaviour is that the monopolist charges \( 2V_M \) for the tied product in period 1, the monopolist invests and sells an upgraded complementary product in period 2 for \( \lambda \), and consumers purchase the tied product from the monopolist in period 1 and the upgraded complementary product from the monopolist in period 2. This yields monopoly profits the same as if there were no rival, i.e., \( \pi_M = \pi_M^* = N(2V_M + \lambda - \epsilon_p - 2\epsilon_c) - Z \).

Suppose now that the monopolist ties and leases its products. Then again the rival is not able to sell or lease its complementary product. Because consumers are identical and \( N\lambda > Z + N\epsilon_c \), in this case equilibrium behaviour is that the monopolist charges \( V_M \) for the tied product in period 1, the monopolist invests and leases an upgraded tied product in period 2 for \( V_M + \lambda \), and consumers lease the tied product from the monopolist in period 1 and the upgraded tied product from the monopolist in period 2. This also yields monopoly profits the same as if there were no rival, i.e., \( \pi_M = \pi_M^* = N(2V_M + \lambda - \epsilon_p - 2\epsilon_c) - Z \).

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 period 1. One equilibrium to the resulting period-2 subgame is that only the rival invests, the monopolist charges \( V_M + \lambda - c_c - (Z/N) \) for the primary product, \( c_c + \varepsilon \) for its complementary product, the rival charges \( V_R - V_M + c_c + (Z/N) \) for its complementary product, and consumers lease primary units from the monopolist and upgraded complementary units from the rival (one reason this is equilibrium behaviour is that, if the monopolist chose to invest, then there is necessarily an equilibrium to the period-2 pricing game in which period-2 monopoly profits are no higher). This yields period-2 profits for the monopolist equal to \( N(V_M + \lambda - c_c) - Z \).

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 period-1 behaviours the equilibrium to the period-2 subgame is the one described above in which the monopolist earns period-2 profits equal to \( N(V_M + \lambda - c_c) - Z \). Given this, one equilibrium set of period-1 behaviour is that the monopolist charges \( V_M - c_c \) for the primary product, \( c_c + \varepsilon \) for its complementary product, the rival charges \( V_R - V_M + c_c \) for its complementary product and consumers lease primary units from the monopolist and complementary units from the rival. This is an equilibrium set of period-1 behaviours in that each firm’s choice maximises its profits over the two periods given the other firm’s pricing behaviour. This yields period-1 profit for the monopolist equal to \( N(V_M - c_p - c_c) \) and profit over the two periods equal to \( N(2V_M + \lambda - c_p - 2c_c) - Z \).

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 \( \pi_M = \pi_M^* = N(2V_M + \lambda - c_p - 2c_c) - Z \). But similar arguments yield that for each of the other three possibilities associated with the monopolist choosing not to tie, that is, both firms sell, the monopolist leases and the rival sells, and the monopolist sells and the rival 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 maximises 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 \( \pi_M^* \), 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 period 2 is that only the rival invests, pricing is such that the rival earns period-2 profits equal to zero, and the monopolist receives the remaining period-2 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 period-2 situation not investing can result in profit for the rival less than or equal to zero.

Given this, consider period 1 and suppose that, for any period-1 set of behaviours, the equilibrium to the period-2 subgame is the one described above in which the rival invests and earns zero profits. Then the rival’s period-1 behaviour will maximise period-1 profits. Taking all this as given, one equilibrium set of behaviours for period 1 is that both firms lease, the monopolist charges \( V_R - c_c \) for its primary product, \( c_c + \varepsilon \) for its complementary product, the rival charges \( c_c \) for its complementary product, and consumers lease primary units from the monopolist and complementary units from the rival.

This is equilibrium period-1 behaviour because over the two periods the monopolist is earning all the potential surplus so there cannot be an alternative period-1 behaviour for the monopolist that is better, while given the monopolist’s period-1 strategy there is no alternative behaviour for the rival that yields strictly positive profits over the two periods. This shows that there is one equilibrium to the full game characterised 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 surplus sharing assumption, we have that the monopolist prices the primary good at \( V_M + \lambda - c_c + (1 - \rho) \) (\( V_R - V_M + \Delta \)), the rival prices its upgraded complementary good at \( \rho(V_R - V_M + \Delta) + c_c \) and consumers lease the primary good from the monopolist and the upgraded complementary good from the rival (the monopolist prices its upgraded complementary good high enough that this price does not serve as a constraint on the price the rival charges for its upgraded complementary good). This yields period-2 profits for the monopolist equal to \( N[V_M + \lambda - c_c + (1 - \rho) (V_R - V_M + \Delta)] - Z \) and period-2 profits for the rival equal to \( N\rho(V_R - V_M + \Delta) - Z \).

The second possibility is that neither firm invests. Given our surplus sharing assumption, we have that the monopolist prices the primary product at \( V_M + (1 - \rho) (V_R - V_M + c_c + \Delta) \), the rival prices its complementary good at \( \rho(V_R - V_M + \lambda + \Delta) + c_c \) and consumers lease the primary good from the monopolist and the complementary good from the rival (as before, the monopolist’s complementary-good price is high enough that it does not serve as a constraint). This yields period-2 profits for the monopolist equal to \( N[V_M + c_c + (1 - \rho) (V_R - V_M + \lambda + \Delta)] \) and period-2 profits for the rival equal to \( N\rho(V_R - V_M + \lambda + \Delta) - Z \).

The third possibility is that the rival invests and the monopolist does not. Given our surplus sharing assumption, we have that the monopolist prices the primary good at \( V_M - c_c + (1 - \rho) \) (\( V_R - V_M + \lambda + \Delta \)), the rival prices its upgraded complementary good at \( \rho(V_R - V_M + \lambda + \Delta) + c_c \) and consumers lease the primary good from the monopolist and the upgraded complementary good from the rival (as before, the monopolist’s complementary-good price is high enough that it does not serve as a constraint). This yields period-2 profits for the monopolist equal to \( N[V_M - c_c + (1 - \rho) (V_R - V_M + \lambda + \Delta)] \) and period-2 profits for the rival equal to \( N\rho(V_R - V_M + \lambda + \Delta) - Z \).

The fourth possibility is that the monopolist invests and the rival does not. There are two subcases. The first subcase is that \( V_R \leq V_M + (\lambda - c_c) - \Delta \). In this subcase, the rival does not lease or sell anything in the second period so the firm’s period-2 profit equals zero (when \( V_R = V_M + (\lambda - c_c) - \Delta \) the rival might lease or sell complementary units in period 2 but period-2 profit still equals zero).

The second subcase is that \( V_R > V_M + (\lambda - c_c) - \Delta \). Given our surplus sharing assumption, in this case the monopolist prices the primary product at \( V_M + \lambda + (1 - \rho)[V_R - V_M - (\lambda - c_c) + \Delta] \), the rival’s complementary-good price is \( \rho(V_R - V_M - (\lambda - c_c) + \Delta) \) and consumers lease the primary good from the monopolist and the complementary good from the rival (as before, the monopolist’s complementary-good price is high enough that it does not serve as a constraint). This yields period-2 profits for the monopolist equal to \( N[V_M + \lambda - c_c + (1 - \rho)[V_R - V_M - (\lambda - c_c) + \Delta]] - Z \) and period-2 profits for the rival equal to \( N\rho(V_R - V_M - (\lambda - c_c) + \Delta)] \).

Now consider the investment decision. Suppose the rival thinks the monopolist will not invest. Then from above the return to the rival investing is \( N\rho(\lambda - c_c) - Z \) so the rival invests given our parameter restriction \( N\rho(\lambda - c_c) > Z \). Suppose the rival thinks the monopolist will invest. Then from above the return to the rival investing is at least \( \min\{N\rho(\lambda - c_c) - Z, N\rho(V_R - V_M + \Delta) - Z \} \) which is strictly positive given \( \Delta \) sufficiently large and our parameter restriction \( N\rho(\lambda - c_c) > Z \), so again the rival invests. That is, the rival invests independent of whether or not it thinks the monopolist will invest. Now consider the monopolist’s choice given it knows that the rival will invest. Then from above the return to the monopolist investing is \( N\rho(\lambda - c_c) - Z \). Suppose the rival invests. 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 period 1 it leases its tied product for \( V_M \) and earns \( N(V_M - c_p - c_c) \). Given our parameter restrictions, in period 2 the monopolist invests and
the rival does not, the monopolist leases the upgraded tied product for \( V_M + \lambda + \Delta \), and the monopolist earns \( N(V_M + \lambda + \Delta - c_\lambda) - Z \). The monopolist’s profit over the two periods is \( N(2V_M + \lambda + \Delta - c_p - 2c_\lambda) - Z \).

Now suppose the monopolist ties and sells. Then in period 1 it sells its tied product for \( 2V_M + \Delta \) and earns \( N(2V_M + \Delta - c_p - c_\lambda) \). Given our parameter restrictions, in period 2 the monopolist invests and the rival does not, the monopolist sells the upgraded complementary product for \( \lambda \), and the monopolist earns \( N(\lambda - c_\lambda) - Z \). The monopolist’s profit over the two periods is again \( N(2V_M + \lambda + \Delta - c_p - 2c_\lambda) - Z \).

Now suppose the monopolist does not tie. We first consider what happens when the monopolist does not tie and leases. We start with period 2. There are three possibilities concerning what is true at the beginning of period 2. The first possibility is that the monopolist leased primary and complementary units in period 1. If \( \lambda \) and \( \Delta \) are both sufficiently large, then in period 2 only the monopolist invests, the monopolist leases primary and complementary units for a combined price of \( V_M + \lambda + \Delta \), the monopolist earns period-2 profits equal to \( N(V_M + \lambda + \Delta - c_\lambda) - Z \), and the rival earns period-2 profits equal to zero. The second possibility is that the monopolist leased primary units and the rival leased complementary units in period 1. If \( \lambda \) and \( \Delta \) are both sufficiently large, then in period 2 both firms invest, the monopolist leases primary units and the rival leases complementary units, the monopolist earns period-2 profits equal to \( N(V_M + \lambda - c_\lambda + (1 - p)(V_\lambda - V_M + \Delta)] - Z \), and the rival’s profit equals \( Np(V_\lambda - V_M + \Delta)] - Z \). The third possibility is that the monopolist leased primary units and the rival sold complementary units in period 1. The details of what happens in this case are not required for our argument.

Now consider period 1. If individuals consume the monopolist’s complementary product and \( \lambda \) and \( \Delta \) are both sufficiently large, then we know the rival earns zero over the two periods. Suppose the rival offers to lease its complementary product at a price of zero in period 1. Because prices cannot be strictly negative and the rival has a superior complementary product, this must result in consumers purchasing complementary units from the rival. Given the above, this means profits over the two periods for the rival must be at least equal to \( N(V_M - V_\lambda - \lambda - c_\lambda - 2c_\lambda) - Z \). If \( \Delta \) 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. First consider period 2. There are again three possibilities concerning what is true at the beginning of period 2. The first possibility is that the monopolist sold primary and complementary units in period 1. If \( \lambda \) and \( \Delta \) are both sufficiently large, then in period 2 only the monopolist invests, the monopolist sells upgraded complementary units at \( \lambda \), the monopolist earns period-2 profits equal to \( N(\lambda - c_\lambda) - Z \), and the rival earns period-2 profits equal to zero. The second possibility is that the monopolist sold primary units and the rival sold complementary units in period 1. If \( \lambda \) and \( \Delta \) are both sufficiently large, then in period 2 only the rival upgrades, the rival leases upgraded complementary units, the rival earns period-2 profits equal to \( N(\lambda - c_\lambda) - Z \). The rival’s period-2 profit is again \( N(2V_M + \lambda + \Delta - c_p - 2c_\lambda) - Z \).

Now consider period 1. If individuals consume the monopolist’s complementary product and \( \lambda \) and \( \Delta \) are both sufficiently large, then we know the rival earns zero profits over the two periods. Suppose the rival offers to sell its complementary product at a price of zero in period 1. Because prices cannot be strictly negative and the rival has a superior complementary product, this must result in consumers purchasing complementary units from the rival. Given the above, this means profits over the two periods for the rival must be at least equal to \( N(\lambda - 2c_\lambda) - Z \). But given the participation constraint for consumers, we now have that monopoly profits over the two periods
must be less than or equal to \( N(2V_R + \lambda + \Delta - c_p - 2c_h) - Z - [N(\lambda - 2c_h) - Z] \). If \( \lambda \) 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 \( \lambda \) and \( \Delta \) are both sufficiently large and the monopolist does not tie, then individuals consume the rival’s complementary product in period 1 and the rival’s upgraded complementary product in period 2. Relative to what happens under tying, this improves social welfare by \( 2N(V_R - V_M) \). The only potential decrease in social welfare is that both firms rather than one firm invests which lowers social welfare by \( Z \). If \( 2N(V_R - V_M) > Z \), then the increase dominates, that is, social welfare in equilibrium is lower than social welfare when the monopolist is not allowed to tie.

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