

Product Improvement and Technological Tying in a Winner-Take-All Market

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Abstract

In a winner-take-all duopoly market for systems in which firms invest to improve their products, a vertically integrated monopoly supplier of an essential system component may have an incentive to advantage itself by technological tying; that is, by designing the component to work better in its own system. If the vertically integrated firm is prevented from technologically tying, then there is an equilibrium in which the more efficient firm invests and serves the entire market. However, another equilibrium may exist in which the less efficient firm invests and captures the market. Technological tying enables a vertically integrated firm to foreclose its rival. The welfare implications of technological tying are ambiguous and depend on the asymmetric qualities of the system suppliers and on equilibrium selection.

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1 Introduction

We examine strategic competition in markets for systems that combine one or more component inputs to produce a final output, when one of the components is essential for the final output and is controlled by a single firm. Examples of such markets can be found in information technologies, telecommunications, electricity service and other industries. In these markets a single supplier often controls a component that is essential to a system product that consumers desire. For example, an operating system is an essential component for a consumer who wants to use a computer along with an Internet browser to surf the Internet and use email. The local telephone exchange is an essential component for a consumer who wants both mobile telephony and the ability to complete calls that terminate on the local network. Transmission access is essential for a firm that offers electricity service to residential consumers. The component also could have stand-alone uses. In what follows, the “essential component” is controlled by a monopolist and is essential for a particular system. The system consists of the essential component and a complementary product that can be obtained from the vertically integrated monopolist or from another firm.

Consumers in our model have homogeneous preferences for systems; the firm that supplies the system with the lowest quality-adjusted price wins the entire market. We examine competition in system markets under two strategic scenarios. In the first scenario the monopoly supplier of the essential component cannot prevent or discourage rivals from supplying systems by purchasing the essential component from the monopolist and combining it with their own complementary components. The monopoly supplier of the essential component offers both the essential component as a stand-alone product and systems that combine the essential component with its own complementary product. We show that even on this level playing field, the firm that is the most efficient supplier of systems need not emerge as the market leader.

In the second scenario we consider the incentives of the vertically integrated monopoly supplier of an essential component to prevent competition from suppliers of rival systems. The monopolist could accomplish this in several ways. It could condition the sale of its essential component on a requirement that consumers also purchase its complementary product. This is a tied sale in which the essential component is the tying product and the complementary component is the tied product. The monopolist could engage in a pure bundling strategy by selling only systems and refraining from selling the essential component on a stand-alone basis, or by insisting on a price for the essential component that is so high that rival suppliers of systems could not profitably compete for consumers. These foreclosure strategies based on a contractual tie, pure system sales, or refusals to deal in the upstream product share the disadvantage that they may prevent the monopolist from pursuing potentially profitable stand-alone sales of the essential component. For example, a monopoly supplier of operating systems can have profitable applications for systems that combine the operating system with an Internet browser and for other uses of

the operating system that do not require a browser. A monopoly provider of cable services can profit by offering a package that includes Internet access while also providing basic cable service on a stand-alone basis. As an alternative to contractual tying or pure bundling, the firm could design the essential component to work better with its own system, thereby degrading the performance of rival systems relative to its own. This last strategy is a technological tie. A technological tie may be accomplished by physically integrating a product with another product, in a manner that makes it costly for rivals to sell similar integrated products or by designing an interface or withholding technical information to impede the interoperability of a complementary product.² The technological tie does not prevent the monopoly supplier from pursuing stand-alone sales of the essential component. The design of the product discourages competition from firms that would sell rival systems, while permitting purchases of the essential component for other non-system applications.³

The technological tie effectively gives the monopolist superior access to the essential component. We show that this superior access provides the monopolist with a greater incentive to innovate and is an additional reason why the market structure *ex post* (after firms have invested in quality improvements) need not reflect the most capable supplier of systems *ex ante*. In their antitrust case against Microsoft, the U.S. Department of Justice and several states alleged, among other things, that the integration of Microsoft's operating system and its Internet browser was a technological tie that excluded competition from rival browsers (see, e.g., Gilbert and Katz, 2001).⁴ Microsoft and its defenders argued that its Internet Explorer browser gained market acceptance because it was a superior product (see e.g., Liebowitz and Margolis, 1999), while Microsoft's critics asserted that Internet Explorer benefited from Microsoft's exclusionary practices associated with the distribution and use of its ubiquitous Windows operating system, including the technological tie of Windows and Internet Explorer. We do not suggest that our model represents the Microsoft antitrust case, however the model does show that, while Internet Explorer may have been superior to other browsers *ex post*, this is not sufficient to conclude that the technological tie of Windows and Internet Explorer had no adverse impact on market structure.

The traditional "Chicago School" emphasizes that there is no incentive for technological tying (other than for efficiency reasons) if a monopoly profit for the tying

²See Lessig (2000) for a review of the case law on tying and its applicability to U.S. v. Microsoft.

³For this reason, technological tying in our model is different from a pure bundling strategy. Of course the technological tie could impair the performance of the essential component in other non-system applications, which is a cost that the monopolist would have to consider in its strategy decision.

⁴In another case, the U.S. Court of Appeals for the Federal Circuit held that the manufacturer of a patented biopsy gun engaged in an anticompetitive technological tie when when it redesigned the gun to be incompatible with biopsy needles sold by a competitor. C.R. Bard v. M3 Sys., Inc., 157 F.3d 1340 (Fed. Cir. 1998).

product (in this case, the essential component) can be extracted by charging a profit-maximizing price.⁵ There are reasons, however, why a monopolist may have limited flexibility to charge rivals a monopoly price for an essential component. One possibility is that the component has other uses that consumers value differently, and a non-discriminatory profit-maximizing price fails to fully extract the monopoly profit from consumers who demand a system. Alternatively, regulation (including antitrust scrutiny) may constrain the price that the monopolist can charge for the essential component when it is sold on a stand-alone basis. In such circumstances the monopolist may opt for a mixed bundling strategy, selling the essential component both bundled in a system and on a stand-alone basis, while imposing a technological tie to prevent arbitrage between the two offerings.

The monopolist confronts a trade-off in considering the merits of a technological tie. On the one hand, by limiting rivals' access to an essential component, the monopolist profits by curtailing competition in the market for systems. On the other hand, the technological tie reduces the monopolist's ability to extract rents from more efficient rivals through sales of the essential component. If rivals have a superior ability to innovate, or produce systems that appeal to a large number of consumers, then by providing access the monopolist profits from sales of the component, which firms must purchase to supply a viable system. The technological tying trade-off depends on the price of the essential component. A high price encourages the monopolist to provide efficient access to the essential component, while a low price encourages the monopolist to limit access with a technological tie. Therefore technological tying is likely to be an attractive business strategy for the monopolist if sales of the upstream component are insufficiently remunerative. Nonetheless, technological tying can result from a coordination failure in which the less efficient vertically integrated firm improves its system even for values of the essential component price at or near the monopoly level.

In light of these considerations our analysis focuses on incentives to engage in technological tying conditional on the price of the essential component. We show that if firms are sufficiently similar *ex ante*, the ability to impose a technological tie can significantly impact market structure, prices, and innovation for all values of the component price at or below the monopoly level. In some cases these impacts have negative welfare consequences. If, however, a potential rival is a significantly more efficient supplier of systems, then consistent with the traditional view, we find that the ability to impose a technological tie does not affect market outcomes when the price of the essential component is sufficiently high. Furthermore, if the owner of the essential component is the more efficient supplier of systems, technological tying

⁵Bowman (1957) and Bork (1978), among others, maintain that the owner of an essential input that is used in fixed proportions with another competitively supplied good has no incentive to bundle the input and the complementary good or to tie purchase of the complementary good to the essential input. The argument is that there is a single monopoly profit, which the owner of the essential input can capture by charging a monopoly price.

can increase welfare in some instances by eliminating an equilibrium in which the less efficient system supplier invests and wins the market.

Economides (1998) shows that a price-regulated upstream monopolist participating in a downstream Cournot oligopoly has an incentive for non-price discrimination.⁶ Our analysis develops this theme by analyzing the incentives for and consequences of technological tying for product improvement in a downstream systems market when firms compete on quality and price.⁷ We consider the case of homogeneous consumer preferences over vertically differentiated products. More specifically, we study markets for systems as duopoly games. In our basic “product improvement game”, two firms sell systems comprised of two components: A and B. Firm 1 offers a system comprised of one unit of component A and one unit of its version of component B. Firm 2 purchases component A from Firm 1 at a price w and offers consumers a system that consists of component A and its version of component B. (Alternatively, consumers assemble their own systems by purchasing the essential component from Firm 1 and the other component from either Firm 1 or Firm 2.) Conditional on the wholesale price of component A, rival firms invest in quality improvements of component B (or equivalently, improvements of their systems) and subsequently compete on the price of systems. Firm 2 is assumed to have an initial quality advantage and is the more efficient supplier of systems for the same level of investment in product improvement. In the companion “technological tying game” there is also an intermediate stage in which Firm 1 can act to degrade the quality of Firm 2’s system.

Given that consumers have homogeneous preferences, the market has a winner-take-all character and multiple equilibria of the product improvement game are possible. There always exists an efficient equilibrium of the product improvement game in which Firm 2 improves its product optimally and captures the entire market. If the initial quality advantage of Firm 2 is sufficiently small, then there also exists an inefficient equilibrium in which Firm 1 invests in product improvement and wins the market. In these equilibria, consumers enjoy a positive surplus as long as the losing firm exerts some competitive price pressure on the winner.

In the technological tying game, if the wholesale price is not too large, there is a unique equilibrium in which Firm 1 forecloses competition with an actual, or

⁶In line with Chicago School reasoning, Economides (1998) finds no incentive for non-price discrimination if the input monopolist is a less efficient supplier of systems in the downstream market and the upstream monopoly is unregulated. See also Sibley and Weisman (1998), Bergman (2000), and Economides (2000).

⁷The new vertical foreclosure literature, which includes papers by Salop and Scheffman (1983), Krattenmaker and Salop (1986), Ordover, Saloner and Salop (1990), Riordan (1998), Riordan and Salop (1995), Hart and Tirole (1990), Bolton and Whinston (1991) and Rey and Tirole (2003), identifies incentives for a firm that operates in both upstream and downstream markets to use price and exclusionary contracts to influence downstream competition and to “raise rivals’ costs”. Our analysis can be interpreted as an exploration of technological tying as a raising rivals’ costs strategy.

perhaps merely threatened, technological tie,⁸ improves its product efficiently, and sets a price that fully extracts consumer surplus. In this case, technological tying distorts market structure and reduces consumer welfare by eliminating competition from the more efficient Firm 2. The technological tying game has multiple equilibria for all higher prices of the essential component if the initial quality advantage of Firm 2 is sufficiently small. In one equilibrium, Firm 1 invests and forecloses competition with a technological tie. In the other equilibrium, Firm 2 invests and Firm 1 does not impose a tie. If Firm 2's initial quality advantage is large, then the technological tying game has multiple equilibria for intermediate values of the wholesale price and a unique equilibrium in which Firm 2 invests when the wholesale price is sufficiently close to the monopoly level. When the tying game has multiple equilibria, they are strictly ordered. Both firms are better off, and consumers are no worse off, in the equilibrium in which the more efficient Firm 2 invests.

Farrell and Katz (2000) also study incentives for product improvement in markets for vertically differentiated systems. In their model a monopolist supplies an essential component and competes with others to supply a complementary component to consumers who assemble a system. By "overinvesting" in product R&D for the complementary component, the integrated monopolist squeezes the rents of rival suppliers and is able to charge consumers more for the essential component.⁹ Moreover, the firm prices the essential component to extract monopoly rents after observing the qualities and prices of the competitively supplied components. While Farrell and Katz (2000) do not explicitly address incentives for technological tying, their analysis reinforces the Chicago School conclusion that there is no reason for technological tying if the monopolist can extract rents effectively by adjusting the price of the essential component. In contrast, we assume that the wholesale price of the essential component is determined prior to systems market competition, and focus on cases in which the wholesale price fails to fully extract monopoly rents from the systems market.

Choi and Stefanadis (2001) also model competition in markets for systems. In their model an incumbent monopolist sells two complementary components and potential entrants invest under uncertainty to introduce new lower-cost versions of one or both of the components. Tying by the incumbent deters entry into both component markets and strengthens the incumbent's incentive to invest in cost reduction. As in Farrell and Katz (2000), component prices are determined after firms make their investment decisions, and the incumbent can price an essential component to extract rents if low-cost entry occurs in only one of the two markets. Thus, the incentive to

⁸When a merely threatened technological tie does the job, Firm 2 is foreclosed by a price squeeze, meaning that the wholesale price is prohibitive compared to Firm 2's equilibrium quality. Firm 2 declines to invest in product quality because it rationally believes that Firm 1 would foreclose a competitive product with a technological tie.

⁹Choi, Lee, and Stefanadis (2003) shows a similar result. See also Bolton and Whinston (1993) and Kranton and Minehart (2004) for related models of strategic over-investment.

tie in Choi and Stefanadis (2001) depends on a risk of entry into both component markets. Moreover, in further contrast to our technological tying game, tying in their model requires a commitment to tie prior to firms' investment decisions.

Section 2 describes the structure of the market for systems and the technology for product improvement. This section introduces the assumptions that systems are vertically differentiated, Firm 2 is the higher quality supplier of systems when neither firm invests and that, by investing, Firm 1 can leapfrog Firm 2's initial quality advantage. These assumptions frame the policy issues by defining an environment in which Firm 1 can use its control over access to the essential component to influence investment incentives and thereby distort market outcomes. Section 3 introduces the product improvement game and identifies the pure strategy equilibria. Section 4 does the same for the technological tying game. Section 5 examines the welfare implications of the different equilibria, and Section 6 considers the competitive consequences of several variations on our basic theme, such as assigning the initial quality advantage to Firm 1, assuming that a firm exits the market if it cannot make any sales, and allowing for network effects. Section 7 concludes.

2 Vertical Product Differentiation

There are two firms, indexed $i = 1, 2$. Consumers have a willingness-to-pay for systems that consist of an intermediate good supplied only by Firm 1 (component A) and another complementary good consumed in fixed proportions with the essential component (component B), which either firm can supply. For obvious reasons we call component A the essential component. Firm 2 must have access to the essential component to compete in the systems market. As explained further below, the essential component can be sold also on a stand-alone basis separately from systems.

Systems are differentiated in quality, which is partly exogenous and partly endogenous. Each of M identical consumers demands a single system. A consumer's willingness-to-pay for a system consisting of components A and B from firm i is

$$q_i = \gamma_i + q(r_i), \tag{1}$$

where γ_i is an exogenous quality parameter specific to systems sold by Firm i and the endogenous variable r_i is Firm i 's investment in R&D to improve the quality of its system (or, equivalently, the quality of its component B). The quality investments affect the value of systems, but do not affect the value of the stand-alone component. For analytical convenience, we assume that there are no additional variable costs of producing systems.

It is convenient to reinterpret equation (1) as Firm i choosing a level of quality improvement

$$z_i = q_i - \gamma_i$$

by incurring an R&D cost

$$r_i = r(z_i).$$

We maintain several assumptions.

A1: The symmetric R&D cost function $r(z)$ is increasing, strictly convex, twice differentiable, and satisfies $r(0) = r'(0) = 0$.

The first assumption implies that there is a unique z^M that maximizes the net benefits from quality improvement $zM - r(z)$ and is the solution to $r'(z^M) = M$. Thus z^M is the efficient level of quality improvement for a firm selling to the entire market, yielding a net return $z^M M - r(z^M) > 0$.

A2: $\gamma_2 - \gamma_1 > 0$.

The second assumption implies that Firm 2 is the more efficient supplier of systems for any given level of investment in quality improvement.¹⁰ The maximum social surplus in this market is $(\gamma_2 + z^M)M - r(z^M)$, which corresponds to investment of z^M by Firm 2.¹¹ This surplus is fully extracted by Firm 1 with a monopoly wholesale price equal to

$$\bar{w} \equiv \gamma_2 + z^M - r(z^M)/M.$$

A3: $(\gamma_1 + z^M)M - r(z^M) > \gamma_2 M$.

The third assumption implies that Firm 1 can profitably leapfrog Firm 2's initial quality advantage by investing efficiently in product improvement. Although this assumption is not necessary for some of our results, it describes an environment in which investment effects can dominate firm-specific efficiencies, which is the focus of our analysis.

The monopoly good that is an essential component of systems also has a separate stand-alone use that is valuable to a different group of consumers. While M consumers are willing to pay q_i for Firm i 's system, another M' consumers are willing to pay $w < \bar{w}$ for the stand-alone product. The monopolist is unable to charge different

¹⁰This assumption emphasizes the potential social costs of strategic conduct by a vertically integrated supplier. In Section 6 we discuss the alternative case in which Firm 1 is the more efficient supplier of systems.

¹¹More formally, let xM be the allocation of consumers to Firm 1 and $(1-x)M$ the allocation to Firm 2, and let z_1 and z_2 be the firms' investments in quality improvement. The social planner chooses (x, z_1, z_2) to maximize

$$W(x, z_1, z_2) = M[x(\gamma_1 + z_1) + (1-x)(\gamma_2 + z_2)] - r(z_1) - r(z_2).$$

Clearly $W(0, 0, z^M) > W(1, z^M, 0)$. Furthermore, the convexity of $r(z)$ implies that $W(0, 0, z^m) > W(x, z_1, z_2)$ for $x \in (0, 1)$. Therefore, the welfare optimum has $x = 0$, $z_1 = 0$, and $z_2 = z^M$.

prices to these two groups of consumers, and sets a profit-maximizing price equal to w if M' is sufficiently large relative to M . In this case the profit-maximizing price fails to fully extract monopoly profits from the M consumers who demand systems. We make these additional assumptions, and hereafter treat w as the predetermined wholesale price of the monopoly component. An alternative interpretation is that $w < \bar{w}$ is set by regulation.

$$\text{A4: } \bar{w} \geq w \text{ and } M' > \left(\frac{\bar{w}-w}{w}\right)M > 0.$$

The fourth assumption states that the monopoly price of component A when used in a system (\bar{w}) weakly exceeds the monopoly price of the component when sold on a stand-alone basis (w), and that the profit from selling in both submarkets exceeds the monopoly profit from the systems market alone. This implies that if Firm 1 cannot otherwise prevent arbitrage between the markets for systems and the stand-alone component, it would optimally commit to a wholesale price equal to w , earning a profit wM' from stand-alone sales of component A. The profit from stand-alone sales of the component plays no significant role in our analysis, and is ignored hereafter.

Technological tying in the $w < \bar{w}$ case can be understood as a kind of "damaged goods" strategy (Deneckere and McAfee, 1996). The integrated firm segments the consumer market with two products: a basic product (component A) and an enhanced product (component A plus its own complementary component B). A crucial feature of this strategy is that the basic product is incompatible with enhancements offered by firms. Otherwise, the strategy would fail to segment the market effectively. For example, a cable system operator might sell a basic product consisting of cable TV service, and an enhanced product consisting of cable TV service bundled plus broadband Internet service, while preventing or degrading access to alternative Internet services on its cable modem platform.¹²

We compare the subgame perfect Nash equilibria of two different game forms. In the "product improvement game", competition proceeds in two stages. In the first stage the firms simultaneously and independently choose quality improvements z_i at cost $r(z_i)$. In the second stage the firms simultaneously and independently set prices $P_i \geq w$ after observing each other's quality. The "technological tying game" amends the product improvement game by introducing an additional stage in which the upstream monopolist can degrade the quality of its rival's system. In the first stage of the technological tying game the firms choose costly quality improvements z_i as in the product improvement game. In the second stage Firm 1 can degrade Firm

¹²Another plausible example of price discrimination enforced through technological incompatibility is Microsoft's licensing of its Windows Media Center software. A recent business report noted that Media Center PC sales surged after Microsoft changed its licensing practices to allow its software to be used on PCs without TV tuners – for people who just want to access other media using the remote control. That reduced the starting price for some Media Center PCs to around \$500. See http://seattlepi.nwsourc.com/business/244568_mediacenter14.html

2's quality by a fixed amount $\delta > 0$. A technological tie always forecloses competition if δ is sufficiently large, which we assume to be the case. In the final stage the firms set prices. In both game forms, the wholesale price is predetermined and consumers purchase optimally after observing retail prices.¹³

The price subgame is the same in both game forms. Consumers observe prices and qualities and choose the product that offers the greatest net utility. Consumers have identical preferences, so Firm i makes sales to all M consumers if $q_i - P_i > \max(q_j - P_j, 0)$. When both products offer the same net utility, consumers are assumed to choose the higher quality product, and if both firms also have the same quality, then consumers are assumed to choose Firm 1.

Equilibrium prices and sales in the market for systems depend on the level of w and product qualities. In an equilibrium of the price subgame, only one firm sells to the entire market. If $q_1 \geq q_2$ and $q_2 \geq w$, then Firm 2 sets price $P_2 = w$ and Firm 1 wins the market at price $P_1 = q_1 - q_2 + w$. A similar result holds for Firm 2 if $q_2 > q_1$ and $q_1 \geq w$. Then Firm 1 sets price $P_1 = w$ and Firm 2 wins the market at price $P_2 = q_2 - q_1 + w$, because w is an opportunity cost of sales for Firm 1 and a direct cost for Firm 2.¹⁴ If $q_2 < w$, then Firm 1 wins the market at price $P_1 = q_1$ even if $q_1 < q_2$. Furthermore, if $q_1 < w \leq q_2$, then Firm 2 wins the market at price $P_2 = q_2$. Thus, the losing firm serves as a competitive check only when the quality of its system is above its opportunity cost. Summarizing, Firm 1 sells to all M consumers at a price $P_1 = q_1 - \max(q_2 - w, 0)$ if $q_1 \geq q_2$ or if $w > q_2$, and Firm 2 sells to all M customers at a price $P_2 = q_2 - \max(q_1 - w, 0)$ if $q_2 > q_1$ and $w \leq q_2$.

We analyze the (pure strategy) equilibria of the product improvement and technological tying games.¹⁵ The equilibria of the product improvement game show that a firm may win the market with a better product even when it would be more efficient for a rival to engage in product improvement. Thus, an *ex post* measure of product superiority can be a misleading indicator of market performance. The equilibria of the technological tying game illustrate the ability and incentives of a firm that controls an essential input to foreclose a more efficient downstream rival from participating in the market for systems. When technological tying is feasible and the wholesale price of the upstream good is insufficiently remunerative, the upstream monopolist has an

¹³In Section 6 we also consider alternative timing for the technological tying game in which the owner of the essential component chooses whether to impose the tie at the first stage of the game, before either firm invests in product improvement.

¹⁴Let xM be Firm 1's sales of systems, with $x \in [0, 1]$. Firm 2's sales are $(1-x)M$. If w is the price of component A, then the respective profits of the two firms are $\pi_1 = (P_1x + w(1-x))M - r(z_1) = (P_1 - w)xM + wM - r(z_1)$ and $\pi_2 = (P_2 - w)(1-x)M - r(z_2)$. Thus, the wholesale price of component A (w), is an opportunity cost of system sales for Firm 1 as well as a direct marginal cost for Firm 2.

¹⁵Pure strategy equilibria are natural outcomes in a winner-take-all market when firms are able to coordinate their investment decisions. In contrast, mixed strategy equilibria describe industry conduct when firms are uncertain about the investment decisions of their rivals. Mixed strategy equilibria are described in Gilbert and Riordan (2003).

incentive to foreclose rivals and substitute its own innovative efforts. Technological tying is potentially costly because it facilitates product improvement and market dominance by a less efficient firm.¹⁶

3 The Product Improvement Game

In the product improvement game, firms invest in quality improvement at stage 1 anticipating a Bertrand-Nash equilibrium of the subsequent price subgame at stage 2. It is immediate that both firms do not make positive investments in equilibrium. One of the firms captures the entire market, leaving the other firm better off not investing. Given our maintained assumptions, there always exists an equilibrium in which the more efficient Firm 2 captures the entire market. A second equilibrium exists if the cost of efficient quality improvement is high relative to Firm 2's initial quality advantage.

Proposition 1 *In the product improvement game:*

(i) *There exists an efficient equilibrium in which Firm 2 invests z^M and Firm 1 invests 0 in quality improvement. Firm 2 sets a price equal to $P_2 = \gamma_2 + z^M - \max(\gamma_1 - w, 0)$, sells systems to all M customers, and earns $\pi_2 = (P_2 - w)M - r(z^M) \geq 0$. Firm 1 sets price $P_1 = w$, sells M units of component A and no systems, and earns $\pi_1 = wM$.¹⁷*

(ii) *There exists a second equilibrium in which Firm 1 invests $z_1 = z^M$ and Firm 2 invests 0 in quality improvement if and only if $r(z^M) \geq (\gamma_2 - \gamma_1)M$. Firm 1 sets price $P_1 = \gamma_1 + z^M - \max(\gamma_2 - w, 0)$, sells systems to all M customers, and earns $\pi_1 = P_1M - r(z^M) \geq 0$. Firm 2 sets price $P_2 = w$, sells no systems, and earns $\pi_2 = 0$.*

(iii) *There are no other equilibria.*

We sketch the proof here. The payoffs to each firm depend on the firms' investment levels and the price of the essential component A. Table 1 below shows payoffs when the firms invest at the efficient level z^M or not at all and the price of component A is greater than γ_2 and less than $\gamma_1 + z^M$. The full proof in the Appendix shows that firms cannot profit by investing other than 0 or z^M . Each cell in the table shows the payoff to Firm 1 followed by the payoff to Firm 2. For example, when both firms invest z^M , Firm 2 wins the market at price $P_2 = q_2 - \max(q_1 - w, 0) = \gamma_2 - \gamma_1 + w$, and

¹⁶If firms were allowed to play mixed strategies, technological tying could be beneficial because it would avoid the inefficiencies of low and redundant investments that can occur in mixed strategy equilibria of the product improvement game. See Gilbert and Riordan (2003). Also, as we discuss in Section 6, technological tying can be beneficial when Firm 1 is the more efficient supplier of systems.

¹⁷This is only Firm 1's profit from systems, including components sold to Firm 2. As noted earlier, Firm 1 also earns a profit from stand-alone component sales that, given A4, has no significant role in our analysis.

earns $\pi_2 = (\gamma_2 - \gamma_1)M - r(z^M)$, while Firm 1 earns $\pi_1 = wM - r(z^M)$. There are two possible equilibria, corresponding to investment by Firm 1 (and not by Firm 2) and investment by Firm 2 (and not by Firm 1). The first equilibrium exists if and only if $r(z^M) \geq (\gamma_2 - \gamma_1)M$, otherwise Firm 2 would leapfrog the less efficient Firm 1 even when Firm 1 invests. When $r(z^M) \geq (\gamma_2 - \gamma_1)M$, the differential quality $(\gamma_2 - \gamma_1)$ is not large enough to compensate Firm 2 for the cost of the quality improvement when both firms invest.¹⁸

Table 1. Firm payoffs when $\gamma_1 < \gamma_2 \leq w \leq \gamma_1 + z^M$

	$z_2 = z^M$	$z_2 = 0$
$z_1 = z^M$	$wM - r(z^M); (\gamma_2 - \gamma_1)M - r(z^M)$	$(\gamma_1 + z^M)M - r(z^M); 0$
$z_1 = 0$	$wM; (\gamma_2 + z^M - w)M - r(z^M)$	$\gamma_1 M; 0$

In the equilibrium in which Firm 1 invests, corresponding to $r(z^M) \geq (\gamma_2 - \gamma_1)M$, Firm 2 makes no sales even though it is able to produce systems more efficiently *ex ante*. By improving its system, Firm 1 endogenously becomes such a formidable competitor that Firm 2 cannot profitably compete once Firm 1's investment in quality improvement is sunk.

The equilibria of the product improvement game show that one cannot rely on *ex post* market structure to infer which firm is the more efficient supplier. Product superiority is endogenous and in our model either firm can invest to become the market leader. In particular, the less efficient Firm 1 can overcome its disadvantage by investing to improve its quality. Having done so, if $r(z^M) \geq (\gamma_2 - \gamma_1)M$, the more efficient Firm 2 cannot profitably invest to win the market even though it can supply a better product than its rival. Thus the “wrong” firm can emerge as the market leader. This indeterminacy exists for any value of the component price, w , even when the vertically integrated firm does not engage in technological tying to impede access by its more efficient rival.¹⁹ The next section explores equilibrium outcomes when such strategies are feasible.

¹⁸If $w < \gamma_2$, the payoffs become $[wM; (\gamma_2 - \max(\gamma_1 - w, 0) - w)M]$ when neither firm invests and $[wM; (\gamma_2 + z^M - \max(\gamma_1 - w, 0) - w)M - r(z^M)]$ when Firm 1 does not invest and Firm 2 invests. Payoffs when Firm 1 invests and Firm 2 does not invest become $[(\gamma_1 - \gamma_2 + z^M + w)M - r(z^M); 0]$. Payoffs when both invest are unchanged from Table 1. If $w > \gamma_1 + z^M$, then Firm 2's payoff becomes $(\gamma_2 + z^M - w)M - r(z^M)$ when both firms invest, and payoffs are otherwise the same as in Table 1. In all cases, the equilibria are the same as for Table 1.

¹⁹We can extend the product improvement game to allow for n firms, each with exogenous initial quality γ_j for $j = 1, \dots, n$. Assume that Firm 1 owns the essential component and $\gamma_1 < \gamma_2 < \dots < \gamma_n$. Define $\Gamma_j \equiv \gamma_j - \gamma_1$ and assume that $\pi^M > \Gamma_n M$, so that Firm 1 can leapfrog the exogenous quality advantage of the most efficient firm. There exists an equilibrium in which Firm 1 invests in quality improvement and wins the market if $r(z^M) \geq \Gamma_n M$. If this condition holds, then there exist other equilibria in which a different firm invests and wins the market, including the most efficient firm. The technological tying game discussed in the next section extends similarly.

4 The Technological Tying Game

Firm 1 can avoid competition from Firm 2 by foreclosing Firm 2's access to component A, which we assume is available only from Firm 1. Foreclosure strategies that are based on a contractual tie, pure system sales, or refusals to deal in the upstream product may be counterproductive for Firm 1 if, as we suppose, there is a separate demand for component A that the upstream monopolist wishes to serve and price discrimination is difficult. In contrast, a technological tie that obstructs the ability of Firm 2 to offer a competitive system, or makes it expensive for consumers to assemble a system using component B from Firm 2, does not limit the ability of the upstream monopolist to pursue a mixed bundling strategy in which the firm both sells systems and makes separate sales of component A in a different market. For simplicity, we assume that a technological tie lowers the quality of a system made with component B from Firm 2 by a fixed amount δ . That is, $q_2 = \gamma_2 + z_2 - \delta$, while $q_1 = \gamma_1 + z_1$ is unaffected by the tie. We assume that technological tying is costless for Firm 1 (other than the indirect cost of lost revenues from sales of component A to Firm 2), and consider only Firm 1's incentives to engage in this activity. Foreclosure is clearly inefficient because it eliminates competition from a more efficient producer. Nonetheless, Firm 1 may profit by foreclosing sales by Firm 2 under some circumstances.

Consider the following three-stage "technological tying game", which amends the basic product improvement game studied in the previous subsection. In stage one the firms choose costly quality improvements z_i as before. In stage two Firm 1 is able to impose a technological tie that degrades Firm 2's quality by an amount $\delta \geq 0$. In stage three the firms set prices $P_i \geq w$. Because the tie is costless to Firm 1, the game can have multiple equilibria when Firm 1 is indifferent to imposing a tie in the second stage. To avoid these trivial outcomes, we assume that Firm 1 does not impose a tie when it is indifferent, which would be the case if technological tying incurred an arbitrarily small cost. Similarly, we assume that Firm 2 sets $P_2 = w$ when it is indifferent to setting w or a higher price.

With vertical product differentiation, Firm 1 may profit by degrading Firm 2's quality only if it wins the system competition; i.e., only if $q_1 \geq q_2 - \delta$. Thus, it is sufficient to focus on technological tying strategies in which the parameter δ is sufficiently large that technological tying always forecloses competition. A sufficient condition is

$$\text{A5: } \delta > \bar{w} - \gamma_1.$$

Firm 2 can make sales in the third stage of the technological tying game only if $q_2(\delta) > q_1$. Firm 1's quality is no less than γ_1 and its price is w if Firm 2 wins the market. If Firm 2 is to make sales, it can charge no more than $P_2 = q_2(\delta) - \gamma_1 + w$

and its profit can be no greater than $(\gamma_2 + z_2 - \delta - \gamma_1)M - r(z_2)$. This is negative if $\delta > \bar{w} - \gamma_1$. Thus Assumption 5 guarantees that there cannot be an equilibrium in which Firm 2 wins the market.

The following proposition establishes the existence of a unique equilibrium outcome of the technological tying game for sufficiently low values of the component price. When $w < \gamma_1 + z^M - r(z^M)/M$, Firm 1 invests z^M and Firm 2 is foreclosed from the systems market by either an actual or threatened technological tie. For low values of w ($w < \gamma_2$), Firm 1 forecloses Firm 2 with a technological tie, in order to eliminate Firm 2's unimproved system as a competitive constraint. For intermediate values of w , Firm 1 does not impose a technological tie in equilibrium because Firm 2 poses no competitive threat unless it invests in product improvement, and Firm 2 is deterred from investing by the credible threat of a technological tie if it were to become a competitive constraint for Firm 1. Although the threat of a technological tie is critical to the equilibrium outcome, whether or not Firm 1 actually imposes a technological tie in equilibrium in this case is irrelevant for profits or welfare if the tie is costless. Finally, note that multiple equilibria can exist when $w \geq \gamma_1 + z^M - r(z^M)/M$. These equilibria are strictly ranked, with both firms better off, and consumers no worse off, when Firm 2 invests.

Figure 1 shows the possible equilibria of the technological tying game for each value of the essential component price, w . The possible equilibria depend in general on the firms' initial quality asymmetry and are shown for $r(z^M) \geq (\gamma_2 - \gamma_1)M$ and $r(z^M) < (\gamma_2 - \gamma_1)M$. These are also the conditions that determine the equilibria of the product improvement game. The following proposition characterizes the equilibria of the technological tying game more formally.

[[PUT FIGURE 1 ABOUT HERE]]

Proposition 2 *In the technological tying game:*

(i) *If and only if $w < \gamma_2$, there exists an equilibrium in which Firm 1 invests z^M , Firm 2 invests 0, and Firm 1 forecloses Firm 2 with a technological tie. In this equilibrium, Firm 1 sets $P_1 = \gamma_1 + z^M$, sells systems to the entire market, and earns $\pi_1 = P_1M - r(z^M)$. Firm 2 sets $P_2 = w$ and earns $\pi_2 = 0$.*

(ii) *If $\gamma_2 \leq w < \gamma_1 + z^M$, there exists an equilibrium in which Firm 1 invests z^M and Firm 2 invests 0. Firm 1 does not impose a technological tie (but credibly threatens to do so if Firm 2 invests), sets $P_1 = \gamma_1 + z^M$, sells systems to the entire market, and earns $\pi_1 = P_1M - r(z^M)$. Firm 2 sets $P_2 = w$ and earns $\pi_2 = 0$.*

(iii) *If $w \geq \gamma_1 + z^M - r(z^M)/M$, there exists an equilibrium in which Firm 2 invests z^M and Firm 1 invests 0. Firm 1 does not impose a technological tie. Firm 2 sets $P_2 = \gamma_2 + z^M$, sells systems to the entire market, and earns $\pi_2 = (P_2 - w)M - r(z^M)$. Firm 1 sets $P_1 = w$ and earns $\pi_1 = wM$.*

(iv) *There are no other equilibrium outcomes.*

We sketch the proof under the assumption that firms are restricted to invest z^M or 0. The Appendix shows that there is no loss of generality in this restriction because some other investment never is more profitable than the best response from the restricted choice set. When $w < \gamma_2$, Firm 1 prefers to invest z^M and impose a tie. The tie eliminates Firm 2 as a potential competitor and allows Firm 1 to set $P_1 = \gamma_1 + z^M$ and earn its stand-alone value $\pi_1 = (\gamma_1 + z^M)M - r(z^M)$. Firm 2 cannot leapfrog Firm 1's quality because it is foreclosed by the tie, and given that Firm 2 does not invest, Firm 1 is better off with the tie. If Firm 1 chose instead to sell the component to Firm 2, it would earn wM , which by Assumption A3 is less than $(\gamma_1 + z^M)M - r(z^M)$ when $w < \gamma_2$. Investing and foreclosing Firm 2 with a technological tie is therefore a dominant strategy for Firm 1 if $w < \gamma_2$.

Assumption A3 implies that $\gamma_2 < \gamma_1 + z^M$. For $\gamma_2 \leq w < \gamma_1 + z^M$, there is an equilibrium in which Firm 1 invests z^M , Firm 2 does not invest, and Firm 1 does not impose a technological tie. An actual tie is unnecessary for these parameter values because the cost of component A forecloses competition from Firm 2 when it does not invest, and Firm 1 credibly threatens to impose a tie if Firm 2 were to invest sufficiently to become a competitive constraint absent the tie. Firm 1's credible threat to impose a tie in the second stage when $w < \gamma_1 + z^M$ is sufficient to deter investment by Firm 2. Expecting Firm 2 to invest 0, Firm 1 invests z^M and provides a superior system to Firm 2's unimproved system. In this case, no actual anticompetitive behavior is ever observed. Yet market structure is distorted, even when efficient investment by Firm 2 is the unique equilibrium of the product improvement game, i.e., when $(\gamma_2 - \gamma_1)M > r(z^M)$. The more efficient supplier of systems is effectively foreclosed by the ability of the vertically integrated firm to impose a technological tie and its incentive to do so off the equilibrium path.

For $w \geq \gamma_1 + z^M - r(z^M)/M$, an equilibrium exists in which Firm 2 invests z^M and Firm 1 neither invests nor imposes a technological tie. In the second stage, Firm 1 would earn $\gamma_1 M$ if it were to impose a tie, which is less than it would earn by selling the component to Firm 2. In this equilibrium Firm 2 sets $P_2 = \gamma_2 + z^M$, sells systems to the entire market, and earns $\pi_2 = (P_2 - w)M - r(z^M)$. Firm 1 sets $P_1 = w$ and earns $\pi_1 = wM$. This case corresponds closely to the standard Chicago School argument that a firm does not benefit from a technological tie if it can charge the monopoly price for an essential upstream input.

It is interesting that multiple equilibria exist when $\gamma_1 + z^M - r(z^M)/M \leq w < \gamma_1 + z^M$. The equilibrium in which Firm 2 invests efficiently Pareto-dominates the equilibrium in which Firm 1 invests while threatening Firm 2 with a technological tie. In this case, the ability to impose a technological tie is a trap that the tying firm would prefer to avoid. The ability to tie can result in a "bad equilibrium" in which Firm 2 is discouraged from investing to improve its product, because it expects Firm 1 to improve its own system and hence have an *ex post* incentive to foreclose any competition with a technological tie. When $w \geq \gamma_1 + z^M - r(z^M)/M$, Firm 1 has no

profitable use for a technological tie, either threatened or actual, and would be better off relinquishing its ability to impose a tie.

The standard Chicago School argument is that the owner of an essential input has no incentive to foreclose access to the input if it can charge the monopoly price. Since it is possible that $\gamma_1 + z^M > \gamma_2 + z^M - r(z^M)/M = \bar{w}$, this argument must be qualified in the presence of endogenous innovation by the possibility of multiple equilibria even when the wholesale price is set at the monopoly level (\bar{w}). Although in equilibrium the integrated monopolist does not impose an actual technological tie when $w \geq \gamma_1 + z^M - r(z^M)/M$, its mere ability to tie can deter investment by the more efficient Firm 2 and therefore make it impossible to fully extract the monopoly profit. Moreover, the case in which $\gamma_1 + z^M > \bar{w}$ corresponds to $(\gamma_2 - \gamma_1)M < r(z^M)$, and from Proposition 1 this implies that efficient investment would be the unique equilibrium of the product improvement game if tying were not possible. Thus, in this case, there is a policy rationale for prohibiting technological tying, because a prohibition would be Pareto-improving.²⁰ There are however, other plausible modifications of the game in which technological tying can increase welfare in some instances.

5 Welfare

We now consider the welfare implications of the product improvement and technological tying games. The ability of Firm 1 to impose a technological tie obviously threatens social welfare whenever the product improvement game yields an equilibrium in which the more efficient Firm 2 invests. When $r(z^M) < (\gamma_2 - \gamma_1)M$, investment by Firm 2 is the unique equilibrium of the product improvement game and is the efficient market structure, but technological tying destroys the possibility of an efficient market structure when $w < \gamma_1 + z^M - r(z^M)/M$. If $r(z^M) \geq (\gamma_2 - \gamma_1)M$, there are multiple equilibria of the product improvement game. Technological tying does not improve total welfare in this case and can reduce welfare by preventing an efficient equilibrium. Figure 1 illustrates the possible equilibria of the technological tying game and summarizes the cases described in Proposition 2. Together with Proposition 1 we have the following results, which depend on the relative values of $(\gamma_2 - \gamma_1)M$ and $r(z^M)$.

Corollary 1 *If $r(z^M) < (\gamma_2 - \gamma_1)M$, then actual or threatened technological tying strictly reduces social welfare relative to the unique equilibrium of the product improvement game.*

Corollary 2 *If $r(z^M) \geq (\gamma_2 - \gamma_1)M$, then actual or threatened technological*

²⁰AT&T's voluntary divestiture of Western Electric was explained in part by the costs of being both a supplier to downstream firms and a competitor of those firms. Our analysis confirms that the ability to distort downstream competition can indeed be a liability that a monopoly supplier of an essential component would want to avoid.

tying weakly reduces social welfare relative to equilibria of the product improvement game. If the efficient equilibrium is focal, then technological tying strictly reduces social welfare. Otherwise, the ability of Firm 1 to technologically tie is irrelevant for market structure and social welfare (but not for consumer welfare).

Social welfare is obviously at a maximum in the efficient equilibrium of the product improvement game. Nonetheless, consumers (weakly) prefer the inefficient equilibrium to the efficient one. With Bertrand competition, the equilibrium price is the quality level of the investing firm less the margin between quality and cost for the rival firm, provided this margin is positive. This margin determines consumer surplus. The margin is (weakly) larger for Firm 2 because Firm 2's quality level exceeds Firm 1's when neither firm invests. Firm 2 is a greater competitive threat to Firm 1 in the inefficient equilibrium than Firm 1 is to Firm 2 in the efficient equilibrium.²¹ Consumers benefit directly from the greater competitive threat of Firm 2 in the inefficient equilibrium.

Corollary 3. *Consumer surplus is weakly higher in the inefficient equilibrium of the product improvement game than in the efficient equilibrium, and strictly higher when $w < \gamma_2$.*

Technological tying is not in the interests of consumers in this model. It is evident from Proposition 2 that consumer surplus is zero for all values of w in the technological tying game. Actual or threatened technological tying eliminates Firm 2 as a potential competitor in an equilibrium in which Firm 1 wins the market, and a high component price eliminates Firm 1 as a potential competitor in an equilibrium in which Firm 2 wins the market. Thus, consumer surplus is fully extracted in all equilibria of the technological tying game.

Corollary 4 *Consumer welfare is weakly lower in the technological tying game than in the product improvement game. If $w < \gamma_2$, then consumer surplus is strictly lower in the technological tying game relative to the inefficient equilibrium of the product improvement game. If $w < \gamma_1$, then consumer surplus also is strictly lower relative to the efficient equilibrium of the product improvement game.*

Some important caveats are in order. These conclusions depend on the assumption that Firm 2 is initially the more efficient system supplier. We consider the case in which Firm 1 is initially more efficient in the next section. Furthermore, the above welfare analysis is premised on the assumption that the wholesale price is the same in the product improvement game and the corresponding technological tying game. The assumption is most plausible when the wholesale price is determined by regulation. The assumption also makes sense for our specific model in which the wholesale

²¹The surplus that each consumer enjoys from the purchase of system i is $CS_i = q_i - P_i$. The equilibrium price of system i when $q_i > q_j$ is $P_i = q_i - \max(q_j - w; 0)$. Therefore, consumer surplus when Firm i wins the market is $CS_i = \max(q_j - w, 0)$. It follows that $CS_1 \geq CS_2$, with a strict inequality when $\gamma_2 > w$.

price is determined by the monopoly price of the component in its stand-alone use. More generally, the non-discriminatory profit-maximizing price that the upstream monopolist would charge without technological tying is a compromise between the profit-maximizing prices for each possible use. Technological tying allows the firm effectively to set a higher price for the component when it is used as part of a system, and a lower price for other uses. When such a mixed bundling strategy is profitable, a prohibition against technological tying could cause the price for alternative uses to increase, depending on price elasticities. This possibility tempers the case against technological tying.

6 Some Extensions

In this section we consider several modifications to the product improvement and technological tying games. These include reversing the assumption that Firm 2 has the initial quality advantage, allowing the losing firm to exit the market, reversing the order of moves in the technological tying game, and allowing for systems with network effects.

6.1 Firm 1 has the initial quality advantage

The analysis of the equilibria of the product improvement game is little changed if Firm 1 has the initial quality advantage. Suppose $\gamma_1 > \gamma_2 \geq 0$ and define $\bar{w}_1 \equiv \gamma_1 + z^M - r(z^M)/M$. Payoffs are shown in Table 2 below for $\gamma_1 \leq w \leq \min(\gamma_2 + z^M, \bar{w}_1)$. There is an efficient equilibrium in which Firm 1 invests z^M and Firm 2 does not invest. This is the unique equilibrium if $r(z^M) < (\gamma_1 - \gamma_2)M$. There is a second equilibrium in which Firm 2 invests z^M and Firm 1 does not invest if and only if $r(z^M) \geq (\gamma_1 - \gamma_2)M$. Note that $\bar{w}_1 \leq \gamma_2 + z^M$ if and only if $r(z^M) \geq (\gamma_1 - \gamma_2)M$. Consequently, Table 2 describes the outcomes for all feasible $w \geq \gamma_1$ when $r(z^M) \geq (\gamma_1 - \gamma_2)M$.²²

Table 2. Firm payoffs when $\gamma_2 < \gamma_1 \leq w \leq \min(\gamma_2 + z^M, \bar{w}_1)$

	$z_2 = z^M$	$z_2 = 0$
$z_1 = z^M$	$(\gamma_1 - \gamma_2 + w)M - r(z^M); -r(z^M)$	$(\gamma_1 + z^M)M - r(z^M); 0$
$z_1 = 0$	$wM; (\gamma_2 + z^M - w)M - r(z^M)$	$\gamma_1 M; 0$

²²If $\gamma_2 \leq w < \gamma_1$, Firm 2 earns $(\gamma_2 + z^M - \gamma_1)M - r(z^M)$ when it invests and Firm 1 does not invest. The other payoffs are unchanged. Furthermore, if $w < \gamma_2$, Firm 1's payoff when Firm 2 does not invest is $(\gamma_1 + z^M - \gamma_2 + w)M - r(z^M)$ when it invests and $(\gamma_1 - \gamma_2 + w)M$ when neither firm invests.

If $r(z^M) < (\gamma_1 - \gamma_2)M$, then there are outcomes in which Firm 2 is foreclosed by a high component price when both firms invest and $\gamma_2 + z^M \leq w < \bar{w}_1$. The efficient equilibrium in which Firm 1 invests is also unique in this case.

In the technological tying game, if Firm 1 has the initial quality advantage, then for $w < \gamma_2$ there is an equilibrium in which Firm 1 invests z^M , Firm 2 does not invest, and Firm 1 forecloses Firm 2 with a technological tie. Firm 1 sets $P_1 = \gamma_1 + z^M$, sells systems to the entire market, and earns $\pi_1 = P_1 M - r(z^M)$. Firm 2 sets $P_2 = w$ and earns $\pi_2 = 0$. For $w \geq \gamma_2$, there is a second equilibrium in which Firm 1 invests z^M , Firm 2 does not invest, and Firm 1 does not impose a technological tie. The component price eliminates Firm 2 as a potential competitor when it does not invest, and if Firm 2 were to invest, then Firm 1 would have a credible threat to impose a tie. Payoffs are the same as in the first equilibrium. These are the only equilibrium outcomes of the tying game when Firm 1 is the more efficient supplier of systems. For example, if Firm 2 invested z^M , Firm 1 could earn no more than $(\gamma_2 + z^M)M - r(z^M)$ by selling the component to Firm 2; but by investing and imposing a technological tie in the second stage of the game it would earn $(\gamma_1 + z^M)M - r(z^M)$. When Firm 1 has the initial quality advantage, the technological tie has the beneficial result of selecting the efficient equilibrium of the product improvement game.²³

6.2 Losing firm exits the market

Our analysis assumed that a firm can be a competitive threat even if it does not win the market. By “waiting in the wings” a lower-quality firm can discipline the price charged by a higher-quality firm, provided that it is not otherwise foreclosed from competing. An alternative assumption is that a firm exits the market if it cannot make sales.²⁴ This implies that Firm 2 exits the market and is not a competitive constraint if Firm 1 invests and Firm 2 does not, or if it is foreclosed by a high component price. Similarly, Firm 1 does not constrain the prices charged by Firm 2 if Firm 2 invests and wins the market. Table 3 shows the payoff matrix for the product improvement game for investments z^M or 0 under this alternative exit assumption when $w > \gamma_2$. In this case the efficient equilibrium in which Firm 2 invests z^M and Firm 1 invests 0 is the unique equilibrium of the product improvement game. Firm 2 sets a price equal to $P_2 = \gamma_2 + z^M$, sells systems to all M customers, and earns $\pi_2 = (P_2 - w)M - r(z^M) \geq 0$. Firm 1 sets price $P_1 = w$, sells M units of component A and no systems, and earns $\pi_1 = wM$.

Table 3. Firm payoffs when $w > \gamma_2$ and the losing firm exits

	$z_2 = z^M$	$z_2 = 0$
$z_1 = z^M$	$wM - r(z^M); (\gamma_2 + z^M - w)M - r(z^M)$	$(\gamma_1 + z^M)M - r(z^M); 0$
$z_1 = 0$	$wM; (\gamma_2 + z^M - w)M - r(z^M)$	$\gamma_1 M; 0$

²³Plausibly, a technological tie could benefit Firm 1 by increasing γ_1 by δ without changing γ_2 . In this case, Firm 1 would invest and impose a tie if $\gamma_1 + \delta > \gamma_2$. If $\gamma_1 + \delta \leq \gamma_2$, then the equilibrium outcomes are as in Figure 1 with γ_1 replaced by $\gamma_1 + \delta$ and with Firm 1 imposing an actual technological tie whenever it invests.

²⁴Formally, we introduce an additional stage, prior to price competition in which firms can exit the systems market and recover $\varepsilon > 0$. We consider the limiting case as $\varepsilon \rightarrow 0$.

If $w \leq \gamma_2$, Table 3 would be unchanged except for the cell corresponding to no investment by either firm. Payoffs in this case would be $[wM; (\gamma_2 - w)M]$, because Firm 2 would not be foreclosed by a high component price when it does not invest. Thus, if the losing firm exits the systems market, the efficient equilibrium in which Firm 2 invests z^M and Firm 1 does not invest is the unique equilibrium of the product improvement game for all $w < \bar{w}$.²⁵

The assumption that the losing firm exits the market narrows the range of component prices for which Firm 1 would impose a technological tie. One reason for tying in the technological tying game is to eliminate Firm 2 as a competitive constraint when Firm 1 invests and $w < \gamma_2$. The tie is unnecessary if Firm 2 were to exit the market. Thus the alternative exit assumption eliminates the equilibrium described in case (i) of Proposition 2. This leaves two cases of equilibria of the technological tying game. If $w \leq \gamma_1 + z^M$, there is an equilibrium in which Firm 1 invests z^M and Firm 2 does not invest. Firm 1 does not impose a technological tie, sets $P_1 = \gamma_1 + z^M$, sells systems to the entire market, and earns $\pi_1 = (\gamma_1 + z^M)M - r(z^M)$. Firm 2 sets $P_2 = w$ and earns $\pi_2 = 0$. In this equilibrium, the mere threat of a technological tie is sufficient to deter investment by Firm 2. As in the previous model, no actual anticompetitive behavior is observed in this equilibrium, even though the outcome is inefficient and the product improvement game without tying has a unique equilibrium in which the more efficient Firm 2 invests. If $w \geq \gamma_1 + z^M - r(z^M)/M$, there is a second equilibrium in which Firm 2 invests z^M , and Firm 1 does not invest and does not impose a technological tie. Firm 2 sets $P_2 = \gamma_2 + z^M$, sells systems to the entire market, and earns $\pi_2 = (P_2 - w)M - r(z^M)$. Firm 1 sets $P_1 = w$ and earns $\pi_1 = wM$. Either equilibrium outcome could occur if $\gamma_1 + z^M - r(z^M)/M \leq w \leq \min(\gamma_1 + z^M, \bar{w})$.

6.3 Order of moves in the technological tying game

Some of our results flow from the assumption that Firm 1 can impose a technological tie in the second stage of the game, after the firms invest, which makes the threat of a tie an important consideration for firms' investment behavior. This is a reasonable assumption for some competitive environments. For example, a manufacturer of mainframe computers could change the interface protocols that determine how components communicate with the central processor after the manufacturer invests in most of the attributes of the mainframe system. In other environments it is more reasonable to assume that the technological tying decision is made at the same time or before the firm invests to improve the characteristics of its system. For example, the maker of a popular video game console could design the console so that it works with its own games, but not with games supplied by rivals. How would our results change if we reverse stages one and two of the technological tying game? In this

²⁵If we instead assume that Firm 1 has the initial quality advantage and that a firm exits if it does not win the market, then again the efficient equilibrium (in this case the equilibrium in which Firm 1 invests z^M and Firm 2 invests 0) is the unique equilibrium of the product improvement game.

modification of the technological tying game, Firm 1 chooses whether to impose the tie in the first stage. In the second stage both firms make their investment decisions, and they choose prices in the third stage. We refer to this as the “modified technological tying game”.

The possible equilibria of the modified technological tying game differ according to whether $r(z^M)$ is larger or smaller than $(\gamma_2 - \gamma_1)M$. Suppose that $r(z^M) < (\gamma_2 - \gamma_1)M$. In this case the product improvement game described in Proposition 1 has a unique equilibrium in which the more efficient Firm 2 invests z^M . In the modified technological tying game, if $w < \gamma_1 + z^M - r(z^M)/M$, Firm 1 imposes a tie in the first stage and invests z^M in the second stage, and Firm 2 does not invest. Consequently, Firm 1 sells systems at price $P_1 = \gamma_1 + z^M$ and earns $\pi_1 = (\gamma_1 + z^M)M - r(z^M)$, while Firm 2 sets $P_2 = w$ and earns zero. Firm 1 has no incentive to impose a technological tie in the first stage if $w \geq \gamma_1 + z^M - r(z^M)/M$. In this case the equilibrium outcome is the same as in the product improvement game without tying: Firm 2 invests z^M , sells systems at price $P_2 = \gamma_2 + z^M$, and earns $\pi_2 = (P_2 - w)M - r(z^M)$; Firm 1 earns $\pi_1 = wM$. This is more profitable for Firm 1 than investing itself and foreclosing competition from Firm 2. Note that, given $r(z^M) < (\gamma_2 - \gamma_1)M$, the modified technological tying game has a unique equilibrium outcome for every value of w , whereas the technological tying game described in Proposition 2 has multiple equilibria for $\gamma_1 + z^M - r(z^M)/M \leq w \leq \gamma_1 + z^M$. Thus, the modified game avoids the coordination failure of Firm 1 winning the market even though both firms prefer Firm 2 to prevail.

Suppose $r(z^M) \geq (\gamma_2 - \gamma_1)M$. Under this assumption the product improvement game described in Proposition 1 has multiple equilibria. In the modified technological tying game, if $w < \gamma_2$, it is a dominant strategy for Firm 1 to impose a technological tie in the first stage, as this eliminates any possible competition from Firm 2. Therefore, the unique equilibrium outcome when $w < \gamma_2$ is that Firm 1 imposes a tie in the first stage and invests z^M in the second stage, and Firm 2 does not invest. Firm 1 sells systems at price $P_1 = \gamma_1 + z^M$ and earns $\pi_1 = (\gamma_1 + z^M)M - r(z^M)$; Firm 2 sets $P_2 = w$ and earns zero. Firm 1 also prefers the outcome in which it invests when $\gamma_2 \leq w < \gamma_1 + z^M - r(z^M)/M$.²⁶ In this case there are, however, two possible equilibria, only one of which involves a tie. In both equilibria, Firm 1 invests z^M and Firm 2 does not invest. In one equilibrium, Firm 1 imposes a tie in the first stage. Given the tie, Firm 2 has no reason to invest. If Firm 1 were to deviate and not impose the tie, then Firm 2 would invest and win the market in the continuation game. In the other equilibrium, Firm 1 does not impose a tie and Firm 2 does not invest. Given that Firm 2 does not invest and is foreclosed by a high component price, Firm 1 has no incentive to tie in the first stage of the game.²⁷

²⁶Note that by Assumption A3, $\gamma_2 < \gamma_1 + z^M - r(z^M)/M$.

²⁷When $w < \gamma_1 + z^M - r(z^M)/M$, it is a “risk-dominant” strategy for Firm 1 to technologically tie and invest z^M ; *i.e.*, this is Firm 1’s best response when Firm 2 invests or does not invest with

Firm 1 would not impose a tie in the first stage if $w \geq \gamma_1 + z^M - r(z^M)/M$. In this case the possible equilibrium outcomes are the same as in the product improvement game without tying. There are two equilibria, corresponding to investment by Firm 2 or by Firm 1. If Firm 2 invests, its equilibrium price is $P_2 = \gamma_2 + z^M$, it sells systems to the entire market, and it earns $\pi_2 = (P_2 - w)M - r(z^M)$; Firm 1 earns $\pi_1 = wM$. If Firm 1 invests, its equilibrium price is $P_1 = \gamma_1 + z^M$, it sells systems to the entire market, earns it $\pi_1 = (\gamma_1 + z^M)M - r(z^M)$; Firm 2 sets $P_2 = w$ and earns zero.

If Firm 1 is the more efficient firm and could impose a tie in the first stage of the game, it would do so if $w < \gamma_2$ or if $r(z^M) \geq (\gamma_1 - \gamma_2)M$. In the first case the tie eliminates costly potential competition from Firm 2 when Firm 1 invests. In the second case the tie eliminates the possibility of an inefficient equilibrium in which Firm 2 invests. A tie would be unnecessary if the more efficient Firm 1 could impose a tie in the first stage of the game and the less efficient firm would exit the market. In this case the efficient equilibrium in which Firm 1 invests and earns the maximum profit is the unique equilibrium of the product improvement game, so the tie is of no benefit.

6.4 Network effects

Another extension to the model is to allow for network effects. For example, suppose that the perceived quality of the j^{th} system is $q_j = \gamma_j + z_j + v(y_j)$, where y_j is the network of consumers that choose technology j and $v(y_j)$ is a positive network externality with $v(0) = 0$ and $v'(y) \geq 0$. If the networks are fully compatible, and if all consumers purchase a system, then $v(y_j) = v(M)$ for all $j = 1, \dots, n$. With full compatibility, the network externality is common to all systems and raises each system's quality by the same level. As a consequence, the relative payoffs from product improvement are unchanged, assuming that unsuccessful firms remain in the market as potential competitors. Under the assumption of full compatibility, network effects do not change the predictions of the basic product improvement and technological tying games.

If networks are incompatible, multiple equilibria may arise because the values that consumers place on each system depend on the number of consumers who are expected to adopt the system. Thus, in the absence of investments in quality improvement, a less efficient Firm 1 may win the market simply because consumers expect it to win and $\gamma_1 + v(M) > \gamma_2$.²⁸ Moreover, consumer expectations and product improvement incentives are mutually reinforcing. Firm 1 may become the system of choice because each consumer expects other consumers to purchase that system, which in turn creates

equal probabilities (see Fudenberg and Tirole (1991)).

²⁸Thus network effects offer an independent reason for winner-take-all outcomes. With significant network effects, it is possible to introduce a limited amount of consumer heterogeneity into the model without changing our main results.

an incentive for Firm 1 to improve its product, and which in turn deters product improvement by Firm 2 and makes Firm 1's system the more attractive alternative.

7 Conclusions

We have examined the causes and consequences of technological tying in a winner-take-all market for systems. In our basic model a vertically integrated upstream monopolist supplies an essential component to a more efficient independent competitor in the downstream systems market. The two firms compete on price and quality for sales to consumers with homogeneous preferences over these vertically differentiated products. If the wholesale price of the essential component is insufficiently remunerative, then the upstream monopolist has an incentive to foreclose rival systems, either by selling only systems, contractually tying components, or designing an essential component so that it works better with its own systems (technological tying). A technological tying strategy has the advantage of facilitating price discrimination for alternative uses of the essential component. However, a technological tie, or even in some cases the mere threat of a tie, may reduce social welfare by distorting market structure.

The ambiguity regarding the welfare effects of technological tying concerns equilibrium selection when technological tying is infeasible for the vertically-integrated firm, e.g., due to regulation. When firm heterogeneity is not too great, there is an equilibrium of the product improvement game in which the less capable vertically integrated firm improves its quality and wins the market for systems. If this inefficient equilibrium is focal, then technological tying is irrelevant for social welfare. If instead an efficient equilibrium is focal, in which a more capable competitor wins the market, then prohibiting technological tying can increase social welfare by preserving the efficient market structure.

If the wholesale price of the essential component is sufficiently near the monopoly price, then the vertically-integrated upstream monopolist and the more efficient independent downstream firm both prefer the equilibrium in which the upstream monopolist supplies the component and the independent firm wins the downstream market. Nonetheless, if the initial quality difference is not too great, then an equilibrium exists in which the vertically-integrated monopolist forecloses its more efficient rival with a technological tie. This unfortunate coordination failure would be prevented by a ban on technological tying. If, however, the owner of the essential component were the more efficient supplier of systems, then technological tying could increase welfare by eliminating an equilibrium in which a less efficient independent system supplier invests and wins the market. Hence we cannot conclude that a prohibition against technological tying would generally enhance welfare.

The simple vertical differentiation model does not admit equilibria in which both firms invest in product improvement. In a richer model that allows for both vertically

and horizontally differentiated systems, such that some consumers prefer the system sold by Firm 1 and others prefer Firm 2's system even when each has the same (vertical) quality and is sold at the same price, both firms may have an equilibrium incentive to improve their products, and the ability of Firm 1 to technologically tie might reduce Firm 2's market share short of complete foreclosure. The welfare effects of technological tying are more subtle in this case.

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Appendix

A.1. Proof of Proposition 1. Pure strategy equilibria of the product improvement game.

The text shows that, if the firms are restricted to invest either z^M or 0, then there is an equilibrium in which Firm 2 invests z^M and Firm 1 invests 0. In addition, if and only if $r(z^M) \geq (\gamma_2 - \gamma_1)M$, there is another equilibrium in which Firm 1 invests z^M and Firm 2 invests 0.

There are no other profitable deviations when firms' choice sets are unrestricted. Investment by Firm 1 cannot be profitable unless it can win the market from Firm 2, which requires $z_1 \geq z^M + (\gamma_2 - \gamma_1)$ when Firm 2 invests z^M . The best investment for Firm 1 in this case maximizes $\pi_1 = (z_1 - z^M - \gamma_2 + \gamma_1 + w)M - r(z_1)$ subject to this constraint. Convexity of $r(z)$ implies that the constraint binds and Firm 1's maximum deviation profit is $\pi_1 = wM - r(z^M + \gamma_2 - \gamma_1) < wM$. Thus Firm 1 earns less profit by deviating from $z_1 = 0$ when Firm 2 invests z^M , and given that Firm 1 chooses $z_1 = 0$, the profit-maximizing investment for Firm 2 is $z_2 = z^M$. If $z_1 = z^M$ and $z_2 = 0$, Firm 1 has no incentive to deviate and earn $\pi_1 = wM$ by choosing $z_1 = 0$, and has no incentive to choose any other level of quality improvement. If it were profitable for Firm 2 to deviate, then Firm 2 would choose z^M and earn $\pi_2 = (\gamma_2 - \gamma_1)M - r(z^M)$. Therefore, Firm 2 has no incentive to deviate if and only if $r(z^M) \geq (\gamma_2 - \gamma_1)M$.

Nor are there are other candidate equilibria when firms' choice sets are unrestricted. For example, if $\gamma_2 + z^M > \gamma_2 + z_2 \geq \gamma_1 + z_1$, then Firm 2 would deviate profitably by investing z^M instead of z_2 . Alternatively, if $\gamma_2 + z_2 > w$ and $\gamma_2 + z_2 > \gamma_1 + z_1 > \gamma_1$, then Firm 1 would deviate profitably by investing 0 instead of z_1 . Other cases trigger similar deviations to z^M or 0, depending on whether the firm wins the market or not.

A.2. Proof of Proposition 2. Pure strategy equilibria of the technological tying game.

The text identifies the equilibria of the technological tying game for various cases under the assumption that the firms investment choices are restricted to z^M and 0. Alternatively, consider any non-negative investment levels (z_1, z_2) . It is straightforward to show that Firm 1's (Firm 2's) best response to any non-negative $z_2(z_1)$ always belongs to $\{0, z^M\}$, i.e. any $z_1(z_2) \neq \{0, z^M\}$ is strictly less profitable for Firm 1 (Firm 2) than z^M or 0. Consequently, there are no other profitable deviations and no other candidate equilibria when firms' choice sets are unrestricted.

Suppose, for example, that $w \leq \gamma_2$. Then $w < \gamma_1 + z^M - r(z^M)/M$ by A3. If Firm 1 were to invest z_1 and foreclose Firm 2 with a technological tie, then Firm 1 would earn $\pi_T(z_1) = (\gamma_1 + z_1)M - r(z_1)$. This profit function reaches a maximum at z^M . If Firm 1 did not foreclose Firm 2 with a technological tie, then Firm 1 would

earn either wM or $\pi_N(z_1) = (\gamma_1 + z_1 - \gamma_2 - z_2)M - r(z_1)$ depending on whether $z_2 \geq z_1 + \gamma_1 - \gamma_2$ or not. In either case, Firm 1's profit is lower than $\pi_T(z^M)$. Therefore, z^M and technological tying is Firm 1's unrestricted best response to any z_2 .

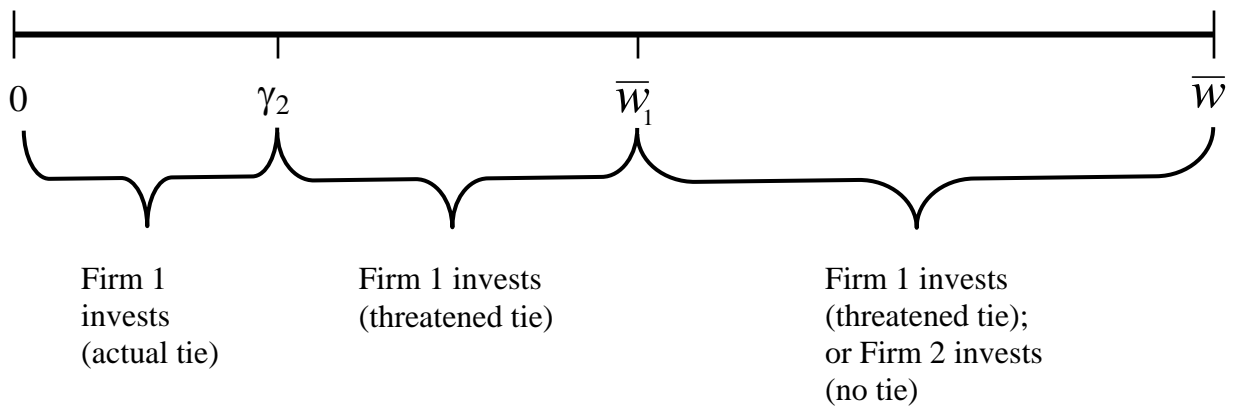
Alternatively, suppose $\gamma_2 \leq w < \gamma_1 + z_1$. Firm 2 would be foreclosed by the component price for $z_2 < w - \gamma_2$, and foreclosed by a technological tie imposed by Firm 1 for any greater investment. Therefore, Firm 2's best response to z_1 and the threat of a technological tie is 0.

Similar analyses of other possible cases confirm that there is no loss of generality in restricting investment choices to $\{0, z^M\}$.

Figure 1

Equilibrium outcomes of the technological tying game for different values of the price of the essential component (w). In these diagrams, $\bar{w}_1 \equiv \gamma_1 + z^M - r(z^M)/M$ and $\bar{w} \equiv \gamma_2 + z^M - r(z^M)/M$.

(a) $r(z^M) \geq (\gamma_2 - \gamma_1)M$:



(b) $r(z^M) < (\gamma_2 - \gamma_1)M$:

