Technology Adoption with Multiple Alternative Designs and the Option to Wait

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Abstract

Technology adoption is one the most important elements of a firm's strategy. In this paper, we address an essential, yet largely overlooked, question: What should a firm do when faced with several alternative proprietary designs of a new technology? In our base case we assume there are two technology designs, each described by an independent stochastic process of technology evolution. We show that, in equilibrium, a buyer chooses the leading technology design as soon as the discounted payoff from doing so is positive. When the option value of waiting is very high, it is jointly optimal to delay adoption. But since sellers cannot commit not to extract all of the buyer's future rents, inefficiently early adoption takes place.

Strategies that improve commitment to low future license fees, such as increasing the number of competitors or cross-licensing, may alleviate the hold up problem. Previous authors stressed the benefit of such commitments in terms of increasing the rate of technology adoption. We present a class of cases when the benefit from commitment is to efficiently delay adoption.

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1 Introduction

Technology adoption is one the most important elements of a firm's strategy — and one of the central sources of competitive advantage. From the point of view of a potential adopter, a key question is when (if at all) to adopt a new technology. If there are several alternative technology designs, then an additional question is which technology design to choose.

There are many examples of new technologies which appear under different alternative designs. In the early and mid 1970s, several versions of the consumer video cassette recorder (VCR) were introduced, of which Sony's Betamax and JVC's VHS were the leading contenders. While each of these designs improved its features (playing length, ability to pre-program), several manufacturers had to choose which standard to adopt. In wireless telecommunications, there are currently two main proprietary designs (CDMA2000, WCDMA), each somewhere between third and fourth generation (see Gandal et al., 2003); and a series of relevant technology users (equipment manufacturers, wireless communications operators), who again must decide which technology design to choose. One of the most heated current technology battles, re-writable DVDs, features two alternative technology designs: Sony's Blue Ray and Toshiba's HD DVD. Both Sony and Toshiba have already attracted a number of manufacturers to their designs.

These three examples — and many other examples of new technology adoption — differ from each other in many respects. Notwithstanding the variety of situations, they all seem to share some common features, which we explore in this paper. First, a new technology becomes available under several different (frequently incompatible) designs. Second, the technology designs are proprietary, so that the conditions for their adoption are determined by their owner — whom we will refer to as the seller. Third, the nature and the size of the investments required to adopt a technology design (beyond licensing fees paid to its owner) imply that potential adopters — also referred to as buyers — choose one of the designs as a long-term commitment. Finally, the value of each technology design evolves over time in an uncertain way — either because improvements are introduced over time or because the various agents gradually learn the value of the technology design.

For a potential technology adopter, the existence of alternative designs leads to a variety of tradeoffs: a static tradeoff between the quality and price of the various alternatives; and a dynamic tradeoff between the early benefits from technology adoption and the option value of waiting — namely the information gathered about the value of each technology design.

From the point of view of a technology design owner, there are two important dimensions: technology improvement and the sale of technology. Frequently, we treat these as two sequential activities: first you create a new technology, then you sell it. Most real-world applications, however, involve concomitant R&D and marketing activities. The state of each technology design evolves over time as the result of various cumulative improvements; and while that process takes place the technology design owner attempts to attract users, who usually make substantial commitments that link them to the current and future versions of the technology design.

In this paper, we study the dynamic process of technology improvement and technology adoption. Specifically, we model the strategic interaction between technology sellers (each owning a different technology design) and technology buyers. We assume that (a) each technology design evolves stochastically over time; (b) in each period sellers offer licensing terms to potential buyers; and (c) a potential buyer must decide when and which licensing terms to accept. We are interested in looking both at the sellers' and at the buyers' strategies: what licensing terms should sellers offer? How long should buyers wait until adopting a technology? Which technology design should they choose?

In our base case, we assume that there are two symmetric sellers, i.e., two firms with identical but independent stochastic processes of technology evolution; and one potential buyer. We show that, in equilibrium, the buyer chooses the leading technology design and does so as soon as the discounted payoff associated with that design is positive. Waiting would give a potential adopter better information regarding the relative merits of each technology, but in equilibrium no delay takes place. In fact, any potential benefits from waiting and observing which technology design evolves faster would be taken away in the form of higher licensing fees.

We also show that, if players are patient enough, then the equilibrium solution is jointly inefficient: an industry value maximizing planner would prefer the buyer to wait and then choose the leading technology design. Key to this result is our assumption that sellers cannot offer contracts contingent on future technology improvements. In fact, if such contracts were available then the equilibrium solution would be socially efficient. As it is, equilibrium play leads to a fundamental hold-up problem: all of the players would be better off if the potential adopter were to delay its decision, but sellers cannot commit to giving the potential adopter some of the benefits from waiting. In other words, the sellers fall prey to a sort of price competition trap: competition not only drives prices down but also leads to inefficiently early adoption decisions.

We consider a variety of extensions of our basic framework. Particularly important is the analysis of the case when there are three or more sellers. In contrast to the two-seller case, we show there are situations where, in equilibrium, a buyer rejects all three offers, in favor of waiting and observing the evolution of each technology design. Intuitively, with three or more sellers there is a chance that two of them will improve beyond their current level and then compete with each other, in which case there is an option value in waiting. Moreover, even if only one seller improves its technology, that seller is no long bound by the buyer's option of purchasing from the rival laggards, but rather by the option of waiting, which in turn implies the seller is unable to fully extract the difference in consumer surplus from immediate adoption — and, again, there is value in waiting.

Although three or more sellers may imply equilibrium waiting, we show that the social optimum (weakly) implies longer waiting than in equilibrium (as in the case of two sellers). In other words, the general pattern is that price competition leads to inefficiently early adoption.

Whereas in static models there is a crucial difference between one and two sellers, in our context the crucial difference is between two and three or more. Moreover, there is an interesting non-monotonic pattern: profits decrease when the number of competitors goes from 1 to 2, but increase as we go from 2 to 3. Intuitively, there are two effects of increasing the number of firms: more competition and less inefficient timing decisions due to hold up; and whereas competition kicks in with two firms, it takes at least three for the hold up problem to be attenuated.

From a strategy point of view, our paper highlights the pitfalls of price competition (Cabral and Villas-Boas, 2005). It stresses that, in addition to reducing the slice of the pie, price competition may actually reduce the size of the pie. The source of this loss in value is the sellers' inability to commit. Therefore, any strategy that might help improve commitment to favorable future licensing terms increases a firm's value. One possible strategy is to increase future competition either by licensing or by cross licensing. This idea has been suggested by several authors as a solution to the hold up problem (e.g., Shepard, 1987; Farrell and Gallini, 1988; Shapiro, 2001). Our contribution here is to show that, in addition to the benefit of encouraging greater investment in new technology, cross licensing may lead to better decisions in the timing of new technology adoption.

■ **Related literature.** Our paper is by no means the first to address strategic issues in the adoption of new technology. References include Reinganum (1981), Fudenberg and Tirole (1985), Riordan (1992), Ghemawat (1993), and many others. One common feature of this literature is competition between potential adopters. Two effects are typically present: preemption incentives, which lead to early adoption, and information spillovers, which lead to late adoption. Equilibrium is typically shown to feature diffusion, with one firm adopting early, the other one late.[1] One

[1] There is also a literature on non-strategic aspects of optimal adoption of a new technology, including the seminal work by Jensen (1982). See Reinganum (1989) for an early survey of the

important distinctive feature of our paper is that we consider strategic interaction on the *supply* side, whereas the above papers take supply conditions as given and focus on the adopter's decision, possibly in competition with a rival adopter.

We are also not the first paper to show that inviting competition may increase value.[2] For example, Shepard (1987), Farrell and Gallini (1988) show that a monopolist (e.g., Intel) might want to license its technology to a competitor (e.g., AMD) as a means of committing not to increase future prices and thus solve a hold-up problem. In our context, additional competition has a similar effect. Sellers cannot commit not to expropriate from buyers all the benefit from waiting and obtaining information about the best technology design. A third competitor allows for at least partial commitment and can thus increase industry value. One important distinctive feature of our paper is that the nature of the hold up problem is inefficiently early adoption, whereas the above papers address the problem of inefficiently low investment or adoption rates.[3]

Lee (2003) and Kristiansen (2006) are closest to our work. Like us, Lee (2003) considers two sellers and a buyer who can decide when to buy. The buyer's valuations for each seller are uncertain and negatively correlated. By waiting, the buyer can obtain more information about the true state. However, Lee (2003) shows that, if sellers compete in prices, then the buyer decides to purchase the better product immediately. The intuition is that differentiation increases sellers' profits because it decreases the externality of competition. Therefore, a buyer prefers not to wait, since time increases differentiation.[4] Kristiansen (2006) shows, like us, that buyers "have inefficiently weak incentives to wait for potentially better products." His analysis stresses the effect that this has on the sellers' incentives to introduce new products: it increases the speed of product introduction beyond socially efficient

literature and Hoppe (2002) for a more recent one. See also the survey by Geroski (2000), which emphasizes new technology diffusion.

[2]More generally, our paper and the literature on inviting competition follow the idea that credible commitments may frequently increase firm value. See Ghemawat (1991).

[3]An additional difference is that, in our framework, the relevant difference is between two firms and more than two firms, whereas in the above cited papers the relevant difference is between monopoly and duopoly.

[4]Mason and Weeds (2004) consider the problem of two competing *buyers*. Like Lee (2003), they assume the bidders' valuations are negatively correlated. They show that, in equilibrium, each agent waits until the state is sufficiently favorable to him; specifically, each agent waits for longer than in an efficient equilibrium. The intuition is similar to Lee's (2003). In Lee (2003), differentiation increases sellers' profits because it decreases the externality of competition. Therefore, a buyer prefers not to wait, since time increases differentiation. In Mason and Weeds (2004), differentiation increases the buyers' profits (for the same reason). Therefore, buyers prefer to wait, since time may increase differentiation.

Of related interest is the literature on information provision in auctions. In particular, Ganuza (2003) shows that a seller has an incentive to release less information to bidders than would be efficient. The intuition is again the same: ignorance promotes competition.

levels.

Our information framework is different from Lee's (2003), and the nature of our main result is also different. As shown by our analysis of the case of more than three sellers, the buyer's decision not to wait is not about product differentiation, rather the hold-up problem described above. With respect to Kristiansen (2006), our analysis focuses primarily on the buyer's decision, not on the sellers' product introduction decisions. We prove a more general result, expand the intuitive analysis of the buyers' incentives to wait, and show how the results critically depend on the number of sellers.

2 Model

Suppose there are two sellers, each offering an alternative design of a new technology, and one buyer. The state, and consequently the value, of each seller's technology design evolves stochastically over an infinite number of periods. Sellers must decide how to price their technology designs in each period. The buyer, in turn, must decide when and which technology design to adopt.

Specifically, we consider the following game. In each period, sellers simultaneously quote prices for their technology designs. These are one-time license fees that entitle the buyer to the current and any future version of the technology design the buyer chooses. Next, the buyer decides whether to adopt (buy one of the technology designs) or rather to wait. We assume adoption decisions are exclusive (one design at most) and irreversible.[5] Finally, Nature determines the evolution of each of the technology designs according to an exogenously given, commonly known, stochastic process.[6] For simplicity, we assume that each technology design can be at two levels, 0 and 1; and that ξ is the transition probability from level 0 to level 1. (In Section 4, we generalize this aspect of the analysis.)

Until adoption takes place, the buyer receives zero payoff each period. Upon adoption of technology design i at time t, the buyer pays the license fee and receives a positive payoff flow of $\sum_{\tau=t}^{\infty} \delta^{\tau-t} \, u(\ell_{i\tau}, \ell_{j\tau})$, where $\ell_{i\tau}$ is the level of technology design i at time τ. Finally, sellers' payoffs are exclusively given by license fees received from the buyer.

To recapitulate, we make a series of assumptions regarding the technology and licensing contracts. First, we assume that sellers cannot commit to future prices

[5] For example, in the context of wireless telecommunications, an industry analysis report states that "a technology evolution path decision is a long-term decision" (Northstream, 2003).

[6] Considering again the case of wireless telecommunications, where GSM and CDMA have been the two main designs, we can distinguish several steps: for the former, GSM, GSM/GPRS, WCDMA, and WCDMA HSDPA; for the latter, CDMA, CDMA2000 1X, CDMA2000 1X EV DO, and CDMA2000 1X EV-DV (Northstream, 2003).

(license fees). Second, we assume that the buyer can only invest in one of the technology designs. Third, we assume that a license sold at time t entitles the buyer to all future versions of the technology design it paid for. Finally, we also assume that each technology design evolves over two levels only and that $u(\ell_{it}, \ell_{jt}) > 0,\ \forall t$. Later in the paper we depart from these assumptions. We then argue that two assumptions are crucial for our results: the sellers' inability to commit to future prices and the buyer's exclusive and irreversible option for one of the technology designs. By contrast, the remaining assumptions we make are generally not important for the qualitative nature of our results. In particular, we could assume a larger number of technology states, some of which with $u(\ell_i, \ell_j) < 0$. In that case, we would denote by state (0,0) the first state such that $u(\ell_i, \ell_j) > 0$. In other words, our analysis should be understood as applying to the period of a technology design such that adoption benefits are positive. Also, we could assume that license fees are paid over time as opposed to upfront; or that different fees are paid as the technology design improves. In that case, our one-time license fee should be understood as the expected discounted value of future license fees.

We are interested in Markov Perfect equilibria of the game played between sellers and buyer. In our context, the sensible definition of a state should include the level of each technology design as well as the history of the buyer's decisions. Since each technology design can be at two levels, 0 or 1, there are effectively eight possible states: four states where the buyer has not opted for one of the designs; and four states where the buyer has committed to one of the designs. We denote by $V(i,j)$ the value function for a buyer who has not committed to a technology design and $U(i,j)$ the value function for a buyer who has committed to technology design i.

Throughout most of the paper, we assume that the payoff from adopting technology design i is independent from the level of development of technology design j. For simplicity, if with some abuse of notation, we denote by $u(\ell)$ the flow of buyer utility from committing to a technology design at level ℓ; and by $U(\ell)$ the buyer's value given that it is committed to a technology design at level ℓ.

Given our assumption that the buyer irreversibly and uniquely commits to one of the technology designs, the four states where the buyer has committed to a particular design are trivial. The buyer's value in such case is given by

$$\begin{aligned} U(1) &= \frac{u(1)}{1-\delta} \qquad (1) \\ U(0) &= u(0) + \delta\Big((1-\xi)\,U(0) + \xi\,U(1)\Big) \\ &= \frac{u(0)}{1-\delta\,(1-\xi)} + \frac{\delta\,\xi\,U(1)}{1-\delta\,(1-\xi)} \end{aligned}$$

$$= \quad \frac{u(0)}{1-\delta\,(1-\xi)} + \frac{\delta\,\xi\,u(1)}{(1-\delta)\,\Big(1-\delta\,(1-\xi)\Big)}. \tag{2}$$

For simplicity, and again with some abuse of notation, we denote by (i,j), $i,j=0,1$, the four states where the buyer has not yet committed to a technology design. We also denote by $p(i,j)$ the price set by a seller whose technology is at level i when its rival's is at level j.

3 Main results

In this section, we formally derive the main results in the paper. The idea is that dynamic price competition leads the buyer to choose one of the technology designs inefficiently early. In particular, the potential size of the pie attainable by sellers is lost in the competitive process of attracting the buyer to its particular technology design.

To reach these results, we solve for the Markov Perfect equilibrium of the game and derive its properties. We solve the game backward, beginning with state $(1,1)$. In this state, Bertrand competition leads to $p(1,1)=0$, and the buyer is indifferent between the two designs. Whichever design the buyer chooses, its payoff is given by $U(1)$.

Suppose now we are in state $(1,0)$. This situation is analogous to Bertrand competition with vertical product differentiation. Seller 1 can offer $U(1)$, whereas seller 0 can only offer $U(0)$. In equilibrium, prices are given by $p(0,1)=0$ and $p(1,0)=U(1)-U(0)$; and the buyer chooses the design at level 1.

Finally, consider state $(0,0)$. Assuming the buyer chooses one of the designs now, we again have symmetric Bertrand competition, implying $p(0,0)=0$ and the buyer randomly choosing one of the sellers and getting $U(0)$. But is it the buyer's optimal strategy to choose one of the designs now? In fact, by waiting the buyer will learn (with positive probability) that one of the designs is progressing faster than the other. Still, a simple argument shows that the buyer will prefer *not* to wait.

By waiting for one period, the buyer expects a payoff of

$$\delta\,\Big((1-\xi^2)\,U(0) + \xi^2\,U(1)\Big)\,. \tag{3}$$

In fact, if neither design improves, we stay at state (0,0) and the buyer gets $U(0)$. If only one design improves, we move to state (0,1) but the buyer again gets $U(0)$. Finally, if both designs improve then the buyer gets $U(1)$. In expected terms, this is inferior to the payoff from adopting the technology now, which is given by

$$U(0) = u(0) + \delta\,\Big((1-\xi)\,U(0) + \xi\,U(1)\Big)\,. \tag{4}$$

We summarize the above in the following result:

Proposition 1 *In a Markov Perfect Equilibrium, sellers set prices* $p(i,j) = 0$ *if* $i \leq j$ *and* $p(i,j) = U(i) - U(j)$ *if* $i \geq j$*; and the buyer always accepts the offer of the seller with the better design.*

In words, Proposition 1 states that the buyer adopts the leading design *without delay.*[7] Starting from state $(0,0)$, by waiting the buyer will gain information about which design is progressing faster. However, such information would be worth little to the buyer: any extra gains from adopting the better design in the future are captured by the owner of that design.

Another way to understand the result's intuition is that, by waiting one period, a buyer will receive a payoff equal to $\min\{U(i'), U(j')\}$, where (i', j') is the state at time $t+1$. But by committing to design i today the buyer gets $u(i)$ today plus $U(i')$ tomorrow. Since $U(i')$ is weakly greater than $\min\{U(i'), U(j')\}$ and $u(i)$ is strictly greater than zero, it follows that accepting today's offer is better. Still another way of presenting the same intuition: by waiting, the buyer expects $U(1)$ next period only if both sellers' technology designs improve. By choosing one of the designs now, however, the buyer expects $U(1)$ next period if that design improves. Clearly, it is more difficult for both designs to improve than for only one to improve.

■ **Equilibrium and efficiency.** What are the properties of the equilibrium in terms of total benefits, for sellers and buyer? From a social point of view (buyers and sellers), prices are simply transfers and should therefore be ignored when finding the optimal solution. If one of the technology designs has reached level 1, then the socially optimal decision is clearly to adopt now that technology, which is what happens in equilibrium.

The question of interest is therefore what to do in state $(0,0)$. By adopting now, we get a social value of $U(0)$. By waiting for one period, expected social payoff is

$$\delta \left((1-\xi)^2 \, U(0) + \left(1 - (1-\xi)^2\right) \, U(1) \right). \tag{5}$$

Notice the contrast with (3). Whereas in equilibrium the buyer only gains when *both* designs improve, from a social point of view it suffices that one of the designs improve. As a result, one can find parameter values such that the value in (5) is greater than $U(0)$ (the value in (4)), and waiting is socially optimal. Specifically, if

$$\gamma \equiv \frac{u(1)}{u(0)} > \Phi(\delta, \xi) \equiv \frac{1 - \delta \, (1-\xi)^2}{(1-\xi) \, \xi \, \delta},$$

[7] Again, we note that we are assuming $u(0) > 0$. If $u(0) < 0$, then there would be good reason for the buyer to delay adoption. Our results should be understood as no delay in adoption beyond the point where technology adoption is profitable.

then it is optimal to wait and the equilibrium solution is inefficient. Not surprisingly, the critical value $\Phi(\delta, \xi)$ is decreasing in δ: the more patient agents are, the more likely waiting is efficient (for a given improvement ratio γ). In the limit when $\delta = 0$, waiting is never optimal.[8] Interestingly, $\Phi(\delta, \xi)$ is *not* monotonic in ξ. In fact, it can be shown that Φ is minimized for $\xi \in (0, \frac{1}{2})$.[9] This is intuitive: if ξ is very small, then technology improvements take very long and waiting has a large opportunity cost. If ξ is very large, then it is very likely that both technologies will improve, and again nothing is gained from waiting.

We summarize the above discussion with the following result:

Proposition 2 *If the value from technology improvement, γ, is sufficiently high, then the equilibrium solution is inefficient: adoption takes place in state (0,0) whereas it would be efficient to delay adoption.*

The intuition for this result is simple. Part of the gain for a buyer from buying today is a transfer from the sellers' future profits. The sellers cannot commit to future prices, in particular they cannot commit not to extract all of the consumer surplus in the future.

■ **Discussion.** Propositions 1 and 2 show that sellers find themselves in a situation where profits are zero even though, potentially, their technology designs might improve greatly in the future—in particular, more than their rival's. The idea that price competition might erode potential seller gains through product improvement or cost reduction is not new. In the context of static price competition, some authors refer to this phenomenon as the Bertrand trap (Hermalin, 1993; Cabral and Villas-Boas, 2005). For example, if all firms' (constant) marginal cost declines by the same amount then equilibrium profits remain at zero. Notice that a Bertrand trap requires symmetry: if only one of the firms improves its product or reduces its cost, then it will reap all of the benefits through a price increase in the exact measure of the quality increase or price reduction.

Our results also show how, *in a dynamic context*, a price game can lead firms into a type of trap. However, there are two important differences with respect to the above mentioned Bertrand trap. First, we allow for the possibility of asymmetry:

[8] It can be shown that $\frac{\partial \Phi}{\partial \delta} = -\frac{1}{(1-\xi)\xi\delta^2} < 0$, which proves monotonicity in δ. Moreover, $\lim_{\delta \to 0} \Phi = \infty$, which implies the second fact.

[9] It can be shown that $\left.\frac{\partial^2 \Phi}{\partial \xi^2}\right|_{\delta=1} = \frac{2}{(1-\xi)^3} > 0$ and $\frac{\partial^3 \Phi}{\partial \xi^2 \, \partial \delta} = -2\,\frac{1-3\xi(1-\xi)}{(1-\xi)^3\xi^3\delta^2} < 0$, which proves convexity with respect to ξ. Finally, solving $\frac{\partial \Phi}{\partial \xi} = 0$ yields the positive solution $\xi = \frac{\sqrt{1-\delta}}{1+\sqrt{1-\delta}}$, which is in $(0, \frac{1}{2})$ for all $\delta \in (0,1)$.

with positive probability, only one of the technologies improves.[10] Second, while a Bertrand trap corresponds to a transfer from sellers to buyer (with no efficiency loss), our result implies that there is a loss in total value. In other words, sellers and buyers together could achieve a higher payoff for all participants.[11]

As mentioned above, the source of inefficiency in the equilibrium timing of technology adoption is the sellers' inability to commit to future licensing terms. In particular, sellers cannot commit not to increase licensing fees when their technology designs improve. A Pareto improvement could be obtained if the buyer were to delay adoption and wait to learn which technology improves faster. This naturally leads to the following question: would a seller be willing to pay a buyer not to adopt immediately? The answer is negative: it can be shown that the gain for the seller is less than what the buyer would require to delay adoption. It can also be shown that unilateral commitment not to increase prices is insufficient to induce the buyer to wait. In fact, if one of the sellers were to make such commitment then the buyer's expected benefit from waiting would be $\delta\,\left(\xi\,U(1)+(1-\xi)\,U(0)\right)$. But this is still lower than what the buyer would get from immediate adoption, $u(0)+\delta\,\left(\xi\,U(1)+(1-\xi)\,U(0)\right)$. Naturally, the inefficiency result implies that *both* sellers would jointly be willing to pay enough to persuade the buyer not to make a decision in the current period. But if sellers can reach an agreement, then there are better solutions (for the sellers). In particular, both sellers would be better off if they increased current prices to the point that the buyer prefers not to make a purchase at (0,0).

Our results have a flavor similar to the classic hold-up problem.[12] If one player has to make an investment and a different player has discretionary power over the future division of payoffs, then the investment level will be inefficiently low. Our results point to a different source of inefficiency: inefficiently early investment. In some sense, the decision of waiting in our model is a type of investment: to forego current benefits in exchange for the option value of waiting. If sellers cannot commit to future prices, then the benefits from the "investment" of waiting are all captured by sellers, which in turn implies that the buyer has no incentive to make the "investment."

The assumption that the buyer only invests in one technology design is obviously important. Instead of making this assumption, we could explicitly model the fixed

[10] Our inefficiency result (Proposition 2) refers to a symmetric state, (0,0). However, in a more general, n-stage technology frontier, inefficient early adoption may also take place at an asymmetric stage. See Section 4 for generalizations of our main results.

[11] So, while in a static context two sellers are sufficient for zero profits and efficiency, in our dynamic context two (symmetric) sellers do indeed receive zero profits, but the equilibrium is inefficient.

[12] See Che and Sakovics (1998) for a summary introduction to the hold-up problem.

cots of investing in a particular technology design. Our assumption would then be equivalent to the assumption that the fixed costs of a particular technology design are very high.[13] By contrast, the assumption that a license fee entitles the buyer to all future versions of the technology design is not important. We could equivalently assume that the buyer must pay for future upgrades in the technology. Equilibrium license values would be different, but the qualitative nature of the results would be the same. What is important is that the buyer be "forced" to commit to a particular technology design. Together with the sellers' inability to commit to future prices, this leads to a hold-up problem, which in turn results in inefficiently early adoption.

4 Generalizations and extensions

Although our model is very simplistic, we believe that its intuition is fairly robust. In this section, we consider several ways in which our basic model and results can be extended. Specifically, we consider the case of technologies which evolve over $n > 2$ stages; asymmetric technology progress functions; horizontal product differentiation; $n > 1$ buyers; the case when one of the technology designs emerges as a dominant design; and the case when intellectual property rights are not perfectly protected. Given its special interest, we leave the case of $n > 2$ sellers to a separate section.

■ ***n* stages of technology evolution.** Proposition 1 assumes that each technology evolves over two stages only (0 and 1). However, the result is true for any finite number of states. Suppose that each technology can be at level $\ell = 0, \ldots, n$ and that $F : S \to S$ gives the probability of going from level i to level i', where $S = \{0, \ldots, n\}$.[14] By subgame perfection, the game considered in Section 3 gives continuation values and strategies for (i, j) with $i, j \geq n - 1$. By mathematical induction, we can extend the analysis further back, showing at each stage that in equilibrium the buyer prefers to adopt immediately. Specifically, suppose we are currently in state (i, j). By waiting one period, a buyer will receive a payoff equal to $\min\{U(i'), U(j')\}$, where (i', j') is the state at time $t + 1$. But by committing to a design today the buyer gets $u(i)$ today plus $U(i')$ tomorrow. Since $U(i')$ is weakly greater than $\min\{U(i'), U(j')\}$ and $u(i)$ is strictly greater than zero, it follows that the buyer is strictly better off by accepting the current offer.

■ **Asymmetric R&D functions.** We have assumed that technology levels are drawn from the same distribution function F (and independently across technology

[13] We don't claim this to be a generally valid assumptions. For example, the Palm Treo is currently available both in Palm and in the Pocket PC versions.

[14] We make the natural restriction that if $i' < i$ then the transition probability is zero.

designs). Suppose alternatively that technologies evolve according to the mapping $F : S_i \times S_j \rightarrow S_i \times S_j$, where S_i is seller i's set of technology levels. This formulation allows both for asymmetry and correlation across sellers. By an argument analogous to that in the previous paragraph, it can be shown that Proposition 1 still holds in this more general stochastic context.

Naturally, the specific equilibrium values of prices and payoffs depend on the particular stochastic process considered. Let us go back to the two seller, two stages model of Section 3. Suppose that technology design progresses from stage 0 to stage 1 with probability $\xi_A > \xi_B$, that is, technology design A is the more promising one. If ξ_A is not too different from ξ_B, and the remaining parameters imply waiting is optimal when the ξ's are equal, then in the asymmetric case we still have inefficiently early adoption. However, differently from the symmetric case, $p_A(0,0)$, the price set by firm A when at state (0,0), is positive; and the buyer adopts design A. If ξ_A is much greater than ξ_B, then the equilibrium solution, early adoption of design A, is efficient.

■ **Imperfect substitutability (horizontal differentiation).** Our model, like the Bertrand model, is based on the assumption of pure vertical differentiation. Suppose instead that the buyer receives a benefit $u(\ell_i) + t\,\epsilon_{it}$ from using technology design i, where ℓ_i is technology level, t an index of horizontal product differentiation ("transportation cost") and ϵ_{it} an i.i.d. preference shock uniformly distributed in $[-\frac{1}{2}, \frac{1}{2}]$. Suppose moreover that $\epsilon_{jt} = -\epsilon_{it}$ and that, at the beginning of each period, the buyer learns its value of ϵ_{it}, whereas the sellers only know its distribution. This is the natural extension of Hotelling's model to our framework. Now we have a model with both vertical product differentiation (through variations in ℓ_i) and horizontal variation (through the values of ϵ_{it}).[15] It can be shown that the equilibrium of this game is continuous in t at $t = 0$. Since our results are based on strict inequalities, it follows that they are robust to perturbations in the value of t away from zero. In other words, while we assume no horizontal differentiation our results are not knife-edged: some horizontal product differentiation is possible.

If the degree of product differentiation is significantly greater than zero, however, then the equilibrium may (efficiently) imply waiting. Consider the two seller, two technology levels case and suppose we are in state (0,1). Suppose moreover that the value of t is sufficiently large that the equilibrium solution is interior (that is,

[15] Our assumption that the preference shocks ϵ are i.i.d. across time significantly simplifies the analysis. Were the buyer characterized by a preference parameter ϵ constant over time we would need to consider the process of Bayesian learning about ϵ by sellers. However, we conjecture the qualitative nature of our point (continuity in t) would remain valid.

first-order conditions apply). Equilibrium prices are then given by

$$p(1,0) = t + \frac{1}{3}\left(U(1) - U(0)\right).$$

This implies that, in state (0,0), a potential adopter expects more than $U(0)$ if the state switches to (1,0). This is different from the $t = 0$ case, in which the potential adopter could only expect an increase in payoff if both sellers improved their technology design. For a given $u(1)$, if δ is sufficiently close to 1, $u(0)$ sufficiently close to zero, and ξ bounded away from 0 and 1; then in equilibrium the buyer rejects $p(0,0) = 0$ and waits until one of the technology designs improves.

■ n **buyers.** Most if not all new technologies have more than one potential buyer. Our assumption that there is only one such potential buyer is made for simplicity. It essentially amounts to assuming that no potential buyer is sufficiently large to the point of influencing other buyers' decisions. If that is the case, then the analysis of one buyer extends to all of n potential buyers.[16]

■ **Dominant designs.** Many instances of new technology adoption involve alternative designs and the eventual emergence of a dominant design. The dynamics of this stochastic process violate several of the assumptions we have made so far; but, as we will show next, the basic intuition of inefficiently early adoption still remains.

Suppose that, with probability ξ, a technology design improves and is chosen as the dominant design; whereas, with probability $1 - 2\,\xi$, the world remains in state $(0,0)$. This formulation differs from the basic model in Section 2 in that the process of technology improvement is negatively correlated across sellers. In fact, in the current formulation state $(1,1)$ is never visited.

Differently from most of the paper, we now must explicitly treat adoption benefits as a function of both technology design levels, that is, $u(i,j)$ and $U(i,j)$. However, given the simple transition process we are considering we can simplify notation by letting $U(1)$ be the value of adopting the winning technology design; $U(-1)$ the value of adopting the losing technology design; and $U(0)$ the value of adopting the technology when both designs are at level zero (and the same for lowercase u).

Notwithstanding these differences with respect to the basic model, we still find the same qualitative results as in Section 3. The situation in states when one of the technology designs has prevailed is trivial. Consider then the case of state $(0,0)$. By choosing one of the designs in the current period, the buyer receives an expected value of

$$U(0) = u(0) + \delta\left((1 - 2\,\xi)\,U(0) + \xi\,U(1) + \xi\,U(-1)\right). \tag{6}$$

[16] See Biglaiser and Vettas (2004) for the case of strategic buyers.

Waiting until next period and then adopting the best technology design leads to an expected payoff of

$$\delta\,\Big((1-2\,\xi)\,U(0)+2\,\xi\,U(-1)\Big)\,,$$

which is clearly less than the value given by (6).[17]

In other words, all else equal it is clearly better to adopt the winning technology design. But not all else is equal when a potential adopter decides to wait. By the time it finds out what the winning design is, it will have to pay a higher license fee, to the point that all of the gains from waiting — and possibly more — are lost to the winning seller.

■ **Property rights.** Implicitly in our analysis is the assumption of perfect IP protection. There are at least two ways in which this assumption can be violated. First, suppose that, with some probability, firm i can emulate the technology improvements of firm j and reach the latter's level of technology development. This essentially implies a more complicated probability transition across technology levels, with added positive correlation between each technology design's motion. As we saw above, our results still hold under asymmetric and non-independent transition processes.

A second way in which the assumption of perfect IP rights can be violated is that, with some probability, a third party be able to sell the same technology design or a lower quality version of it. Under this alternative assumption our results do not hold. In fact, consider the extreme case of perfect imitation. Then prices are always zero and the equilibrium becomes a simple decision problem by the buyer; and the equilibrium solution is trivially socially efficient.

The case of imperfect imitation is particularly interesting. As the discussion in the next section suggests, firm value at state (0,0) is non-monotonic in the degree of imitation it is subject to: profits are zero if there is no imitation or if imitation is perfect; but positive for some intermediate levels of imitation.

5 The case of n sellers

The extension to the case of more than two sellers is sufficiently important to warrant separate treatment. In this section, we first deal with the case of three sellers and then consider the case of a large number of sellers. The $n=3$ case will show that there is a substantial difference with respect to $n=2$. In particular, Proposition 1

[17] In the present calculations we assume that the lagging technology is the best alternative to the winning technology. If that were not the case, then we should replace $U(-1)$ with zero; but the result would still hold.

does not hold with $n = 3$. Together with the results for large n we also obtain an interesting non-monotonicity result with respect to the number of sellers.

Suppose first that there are three sellers. We maintain the same notation but now a state is given by a triplet (i, j, k), each technology design level. As before, we solve the game backwards. Equilibrium strategies in state $(1, 1, 1)$ are straightforward. Each seller sets $p(1, 1, 1) = 0$ and the buyer randomly chooses one of the designs, earning a discounted profit of $U(1)$. Similarly, any state when two designs are at the high technology level lead to $p(1, 1, 0) = p(1, 0, 1) = p(0, 1, 1) = 0$ and a payoff of $U(1)$ to the buyer.

Suppose now we are in state $(1, 0, 0)$. The reasoning from the two-seller case would suggest that laggards price at $p(0, 0, 1) = 0$ and the leader at $p(1, 0, 0) = U(1) - U(0)$. However, that is not necessarily the case. Whereas in the two-seller case the binding constraint on the leader's market power is the option of buying from the laggard in the current period, in the three-seller case the binding constraint may be the option to wait. In fact, it may be that at least one of the laggards improves its design in the next period, in which case waiting would give the buyer a better payoff.

Specifically, by waiting the buyer gets $U(1)$ next period if at least one of the two lagging designs improves. By adopting a lagging technology design today (for a value of $U(0)$), the buyer gets $U(1)$ next period if that design improves. It can be easily shown that if $\xi > \frac{1}{2}$ then the probability of at least one success out of two is greater than the probability of one success out of one. So if ξ is high and $u(0)$ relatively small (or $\gamma > \Phi(\delta, \xi)$, where the latter is defined below), then waiting is better than taking the offer from one of the lagging designs.

If the option of waiting is indeed binding, then the leading design in state $(1, 0, 0)$ will set a price $p(1, 0, 0)$ such that the buyer is indifferent between adopting the leading technology design and waiting. The price is less than $U(1) - U(0)$, so the buyer's value is greater than $U(0)$. In summary: whereas in the two-seller case $V(1, 0) = U(0)$, in the three-seller case it is possible that $V(1, 0, 0) > U(0)$. In fact, in the Appendix we show that $\lim_{\delta\to 1} V(1, 0, 0) = U(1)$. Note however that in both the two and three seller cases there is no waiting at the state when there is one leading technology design.

Suppose now we are in state $(0, 0, 0)$. Suppose moreover that the values of ξ, δ, γ are such that $V(1, 0, 0) > U(0)$, that is, waiting is a binding constraint for the leading seller in state $(1, 0, 0)$. Then by waiting at state $(0, 0, 0)$, a buyer expects more than $U(0)$ in the next period if at least *one* technology improves. By choosing one of the (level 0) designs now, the buyer expects more than $U(0)$ next period if that particular design improves tomorrow. Clearly, one success out of one is less likely than at least one out of three. Waiting implies foregoing a benefit $u(0)$ today.

It follows that, if this is not too large, then the buyer is better off by waiting.

In the Appendix, we formally derive the strategies that form the Markov Perfect Equilibrium described above, both the sellers' pricing strategies $p(i,j,k)$ and the buyer's adoption strategy $a(i,j,k)$. They are given by

$$\begin{aligned}
p(1,1,i) &= 0 \quad (i=0,1) \\
p(1,0,0) &= \begin{cases} \frac{u(1)-u(0)}{1-\delta(1-\xi)} & \text{if} \quad \gamma \leq \Phi(\delta,\xi) \\ \frac{u(1)}{1-\delta(1-\xi)^2} & \text{if} \quad \gamma > \Phi(\delta,\xi) \end{cases} \\
p(0,0,0) &= 0 \\
a(0,0,0) &= \begin{cases} N & \text{if} \quad \delta > \Gamma(\xi) \quad \text{and} \quad \gamma \geq \Psi(\delta,\xi) \\ Y & \text{otherwise} \end{cases} \\
a(i,j,k) &= Y \quad \text{if} \quad (i,j,k) \neq (0,0,0)
\end{aligned}$$

where

$$\begin{aligned}
\gamma &\equiv \frac{u(1)}{u(0)} \\
\Phi(\delta,\xi) &\equiv \frac{1-\delta\,(1-\xi)^2}{(1-\xi)\,\xi\,\delta} \\
\Psi(\delta,\xi) &\equiv \frac{\left(1-\delta\,(1-\xi)^3\right)\left(1-\delta\,(1-\xi)^2\right)}{\left(\xi\,(3-2\xi)-\delta\,\xi\,(2-2\,\xi^2+\xi^3)-1+\delta\right)\delta\,\xi} \\
\Gamma(\xi) &\equiv \frac{1-2\,\xi}{(1+\xi)(1-\xi)^2}.
\end{aligned}$$

We now summarize the most salient features of the three-seller equilibrium:

Proposition 3 *Suppose there are three alternative technology designs. If the gains from innovation, γ, and the discount factor, δ, are sufficiently large, then*

- *At state $(1,0,0)$ the leader sets a price that is lower than at state $(1,0)$ in the two-seller case;*
- *At state $(0,0,0)$ the buyer chooses to wait.*

There are two important differences between state $(0,0)$ in the two-seller game and state $(0,0,0)$ in the three-seller game. First, by committing to design A at $(0,0,0)$ a buyer risks the possibility that only B and C (but not A) improve next period, in which case the buyer could have gotten a better design for free. No such regret would take place in the the two-seller case: if the two designs improve, then the buyer will have adopted one of them. Second, even if only B or C improve the buyer gets a better deal from waiting because the leader will not be able to extract all of the added consumer surplus (the binding constraint is not the competitor but the option to wait). By contrast, in the two-seller case a single leader is able to extract all of the consumer surplus.

To conclude, we consider, just as in the two-seller case, the relation between equilibrium and social optimum. In the appendix, we prove that

Proposition 4 *Efficient adoption time is never earlier than equilibrium adoption time.*

Unlike the two-player case, there may be waiting in the three-seller game. When this happens, waiting is also socially optimal. The opposite does not necessarily hold, however. Just like the two-seller case, we can find situations such that there is no waiting in equilibrium though it would be socially optimal to do so.

■ **Discussion.** As we have seen in Section 3, the inefficiency in equilibrium adoption time is due to a hold-up problem: sellers cannot commit not to extract the increased value from waiting and obtaining information on the technology design that is progressing faster. In the current section, we show that an additional competitor partially substitutes for that lack of commitment. Intuitively, with three or more sellers there is a chance that two of them will improve beyond their current level and then compete with each other, in which case there is an option value in waiting. Moreover, even if only one seller improves its technology, that seller is no long bound by the option of buying from the rival laggards, but rather by the option of waiting, which in turn implies the seller is unable to fully extract the difference in consumer surplus from immediate adoption — and, again, there is value in waiting.

The interplay of the forces of competition and hold up has the interesting implication that equilibrium profits are non-monotonic in the number of firms. In fact, under duopoly, firms make zero profits, whereas three sellers may make positive profits ("it takes more than two to tango"). Specifically, suppose that $\delta > \Gamma(\xi)$ and $\gamma \geq \Psi(\delta, \xi)$, so that the three-seller equilibrium is efficient. Then each firm's value is (implicitly) given by

$$V(0,0,0) = \delta \left((1-\xi)^3 \, V(0,0,0) + \xi \, (1-\xi)^2 \, p(1,0,0) \right),$$

which is positive. Finally, if the number of competitors is very large then equilibrium profits are again close to zero. In fact, if there is waiting for $n = 3$, then there is also waiting for $n > 3$, and equilibrium firm value is given by

$$V(0,0,\ldots,0) = \delta \left((1-\xi)^n \, V(0,0,\ldots,0) + \xi \, (1-\xi)^{n-1} \, p(1,0,\ldots,0) \right),$$

which goes to zero as $n \to 0$.

The idea that competition may help firms is not novel. Shepard (1987), Farrell and Gallini (1988) show that attracting competitors may have the advantage of committing a firm not to exploit its customers in the future, thus solving the holdup problem. There is however an important difference with respect to our paper: whereas the previous literature addressed the problem of inefficiently low investment rates, in our framework hold up leads to inefficiently early adoption.

6 Implications for strategy and economic policy

Business strategy is frequently cast in terms of increasing the size of the pie and getting a better slice of it (see for example Brandenburger and Nalebuff, 1996). In that context, price competition is seen as a bad game for sellers because most of the pie is given to buyers. In our paper, we consider a game where price competition not only reduces the slice gotten by sellers *but also reduces the size of the pie itself.*

Lack of commitment and the hold-up problem are at the heart of the inefficiency in the equilibrium timing of technology adoption. We argued in Section 3 that it may be difficult for sellers to directly induce a buyer to delay adoption as efficiency would dictate. However, sellers can directly attack the hold-up problem. One natural way of doing so is to license other future vendors. In particular, cross-licensing may do the job. The commitment problem is that the winning seller cannot commit not to charge the buyer for the increase in value of its technology. But if the rival seller is able to supply the same technology, such alternative supply option may be sufficient for the buyer to delay adoption.

Specifically, suppose that sellers can initially agree on a cross-licensing deal at level l. That is, at any time one seller can use the rival's technology design for the price of l (and resell it). It can be shown that the optimal level from the sellers' perspective is given by

$$\begin{aligned} l^\star &= \frac{\delta\,\xi\,(1-\xi)\;u(1) - \Big(1-\delta\,(1-\xi)^2\Big)\;u(0)}{2\,\Big(1-\delta\,(1-\xi)\Big)\,(1-\xi)\,\xi\,\delta} \\ &= \frac{u(0)}{2\,\Big(1-\delta\,(1-\xi)\Big)}\Big(\gamma - \Phi(\delta,\xi)\Big)\,. \end{aligned}$$

Moreover, the solution of this augmented game is efficient: the buyer delays the adoption decision if and only if it is efficient to do so. To see this, notice that $\gamma > \Phi(\delta,\xi)$ (the condition that a delayed adoption is efficient) if and only if $l^\star > 0$, so that sellers would want to set a cross-license fee which would effectively induce delayed adoption.

The idea of cross-licensing as a solution to commitment problems is not new. Shapiro (2001) and others argue that cross-licensing solves — or at least alleviates — the hold-up problem. Specifically, Shapiro (2001) refers to "the danger that new products will inadvertently infringe on patents issued after these products were designed." In the case we consider, the nature of the problem, and the way in which cross-licensing is a solution to it, are different. The problem is not so much insufficient investment in new technologies, rather that there is inefficiently early adoption. Therefore, our analysis suggests a novel strategic role played by cross-licensing.

But while cross-licensing solves the hold-up problem in the context of our model, it also begs the question of why sellers can commit to license a still undeveloped technology to a competing seller but not to a buyer. For this reason, competition from alternative technologies (as considered in Section 5) may be a more realistic, if partial, solution to the problem of inefficiently early adoption.

In this sense, our result runs somewhat counter the conventional wisdom regarding the value of competing technologies. Especially when network effects are strong, the conventional wisdom is that less is more: fewer alternative technology designs favor the emergence of a single design with all the resulting network benefits. The results and discussion in Section 5 suggest that against this benefit from greater uniformity one must weight the benefit that greater variety has on attenuating the negative effects of the hold-up problem. In other words, having fewer designs speeds up the adoption process — but it also increases the probability of picking the wrong design as dominant design.[18]

[18] Second generation wireless telecommunications standards provide an interesting case study (Gandal et al, 2003; Cabral and Kretschmer, forthcoming): whereas the European Union essentially "forced" the adoption of one design (GSM), in the U.S. the FCC took a more hands-off approach. At one point there were four different designs vying for dominance, with Qualcomm's CDMA eventually prevailing. Our analysis suggests that public policy may lead to the wrong technology design for two reasons. First by artificially restricting to a smaller set of potential designs we may exclude the best. Second, even among the smaller set of allowed technology designs the market selection becomes less efficient.

Appendix

Proof of Proposition 3: Equilibrium strategies in state $(1,1,1)$ are straightforward. Each seller sets $p(1,1,1) = 0$ and the buyer randomly chooses one of the designs, earning a discounted profit of $U(1)$. Similarly, any state when two designs are at the high level lead to $p(1,1,0) = p(1,0,1) = p(0,1,1) = 0$ and a payoff of $U(1)$ to the buyer.

Consider now state $(1,0,0)$. Make the equilibrium hypothesis that the leading seller's binding constraint is the buyer's option of purchasing from a laggard today. Then Bertrand competition implies $p(1,0,0) = U(1) - U(0)$. Substituting (1) and (2) for $U(1)$ and $U(0)$, and simplifying, we get

$$p(1,0,0) = \frac{u(1) - u(0)}{1 - \delta\,(1-\xi)}.$$

The buyer's expected payoff from waiting is then given by

$$\begin{aligned}&\delta\left((1-\xi)^2\left(U(1) - p(1,0,0)\right) + \left(1-(1-\xi)^2\right)U(1)\right)\\ &\quad = \delta\left((1-\xi)^2\,U(0) + \left(1-(1-\xi)^2\right)U(1)\right).\end{aligned}$$

Buying now from a laggard gives the buyer an expected payoff of

$$U(0) = u(0) + \delta\left((1-\xi)\,U(0) + \xi\,U(1)\right).$$

Our equilibrium hypothesis thus requires that

$$u(0) + \delta\left((1-\xi)\,U(0) + \xi\,U(1)\right) > \delta\left((1-\xi)^2\,U(0) + \left(1-(1-\xi)^2\right)U(1)\right),$$

which is equivalent to

$$\gamma \equiv \frac{u(1)}{u(0)} < \Phi(\delta,\xi) \equiv \frac{1-\delta\,(1-\xi)^2}{(1-\xi)\,\xi\,\delta}.$$

(Note that this is the condition that it is efficient not to wait at $(0,0)$ in the two-seller case.)

If $\gamma > \Phi(\delta,\xi)$, then our equilibrium hypothesis does not hold. If the leader were to price $p(1,0,0) = U(1) - U(0)$, then the buyer would prefer to wait. In equilibrium, therefore, the leader sets a price such that the buyer is indifferent between waiting and not waiting, that is, $p(1,0,0)$ solves

$$U(1) - p(1,0,0) = \delta\left((1-\xi)^2\left(U(1) - p(1,0,0)\right) + \left(1-(1-\xi)^2\right)U(1)\right), \qquad (7)$$

which yields

$$p(1,0,0) = \frac{u(1)}{1 - \delta\,(1-\xi)^2}, \tag{8}$$

and an equilibrium value for the buyer of

$$V(1,0,0) = \frac{\delta\,\xi\,(2-\xi)\;u(1)}{(1-\delta)\,\big(1 - \delta\,(1-\xi)^2\big)}. \tag{9}$$

Notice that, if $p(1,0,0) = 0$, then the left-hand side of (7) is greater than the right-hand side. This implies that, regardless of the the value of γ, $p(1,0,0)$ is positive and, in equilibrium, the buyer buys from the leader at state $(1,0,0)$, that is, there is no waiting in equilibrium at state $(1,0,0)$ (as efficiency dictates). Although $p(1,0,0) > 0$, we can also show that $\lim_{\delta\to 1}\; V(1,0,0) = U(1)$. In fact, from (7) we see that $\lim_{\delta\to 1}\; p(1,0,0) < \infty$. However, $\lim_{\delta\to 1}\; U(1) = \infty$. If follows that $V(1,0,0) = U(1) - p(1,0,0) \to U(1)$.

Finally, consider state $(0,0,0)$. Suppose first that $\gamma < \Phi(\delta,\xi)$, so that $V(1,0,0) = U(0)$. Bertrand competition leads to $p(0,0,0) = 0$. Now make the equilibrium hypothesis that the buyer accepts one of the offers. Then $V(0,0,0) = U(0)$, whereas the value from waiting one period is given by

$$\delta\left(\Big((1-\xi)^3 + 3(1-\xi)^2\,\xi\Big)\,U(0) + \Big(3(1-\xi)\,\xi^2 + \xi^3\Big)\,U(1)\right).$$

The equilibrium hypothesis thus requires that

$$U(0) > \delta\left(\Big((1-\xi)^3 + 3(1-\xi)^2\,\xi\Big)\,U(0) + \Big(3(1-\xi)\,\xi^2 + \xi^3\Big)\,U(1)\right), \tag{10}$$

which is equivalent to

$$\Big(1 - \delta\,(1+2\,\xi)\,(1-\xi)^2\Big)\,u(0) > \Big(\delta\,\xi\,(2\xi-1)\,(1-\xi)\Big)\,u(1).$$

This condition is trivially satisfied for $\xi < \frac{1}{2}$, since the coefficient on $u(1)$ is then negative (whereas the coefficient on $u(0)$ is always positive). For $\xi > \frac{1}{2}$, the required condition becomes

$$\gamma < \Lambda(\delta,\xi) \equiv \frac{-1 + \delta\,\Big(1 - \xi^2\,(3-2\,\xi)\Big)}{\delta\,\xi\;(1 - \xi\;(3-2\,\xi))}$$

Computation establishes that

$$\Lambda(\delta,\xi) - \Phi(\delta,\xi) = 2\,\frac{1-\delta(1-\xi)}{\delta\xi(2\xi-1)},$$

which is positive for $\xi > \frac{1}{2}$. If follows that the condition $\gamma < \Lambda(\delta,\xi)$ is weaker than the condition $\gamma < \Phi(\delta,\xi)$; and so, if $\gamma < \Phi(\delta,\xi)$ then there is no waiting at state $(0,0,0)$.

Suppose now that $\gamma > \Phi(\delta,\xi)$, so that $V(1,0,0)$ is given by (9). Make the equilibrium hypothesis that the buyer waits at state $(0,0,0)$. The value from waiting is given by the solution to

$$\begin{aligned} V(0,0,0) \;&=\; \delta\Big((1-\xi)^3\,V(0,0,0) + 3\,(1-\xi)^2\,\xi\,V(1,0,0) + \\ &\qquad\qquad \Big(3\,(1-\xi)\,\xi^2 + \xi^3\Big)\,U(1)\Big). \end{aligned}$$

Our equilibrium hypothesis requires that this be greater than the value from adopting now, that is, $V(0,0,0) > U(0)$. This is equivalent to

$$\begin{aligned} &\delta\,\xi\,(1-\xi)\,\Big(\delta\,(1+\xi)\,(1-\xi)^2 + 2\,\xi - 1\Big)\,u(1) > \\ &> \;\Big(1-\delta\,(1-\xi)^2\Big)\,\Big(1-\delta\,(1-\xi)^3\Big)\,u(0). \end{aligned}$$

Since the coefficient on $u(0)$ is always positive, a necessary condition is that the coefficient on $u(1)$ be positive as well. This is equivalent to

$$\delta > \Gamma(\xi) \equiv \frac{1-2\,\xi}{(1+\xi)(1-\xi)^2}. \tag{11}$$

If this condition is satisfied, then $V(0,0,0) > U(0)$ is equivalent to

$$\gamma > \Psi(\delta,\xi) \equiv \frac{\Big(1-\delta\,(1-\xi)^3\Big)\,\Big(1-\delta\,(1-\xi)^2\Big)}{\Big(\xi\,(3-2\,\xi) - \delta\,\xi\,(2-2\,\xi^2+\xi^3) - 1 + \delta\Big)\,\delta\,\xi}.$$

It can be shown that this condition is stronger than the condition for waiting at state $(1,0,0)$, that is, $\Psi(\delta,\xi) > \Phi(\delta,\xi)$. In fact, computation establishes that

$$\Psi(\delta,\xi) - \Phi(\delta,\xi) = 2\,\frac{\Big(1-\delta\,(1-\xi)^2\Big)\,\Big(1-\delta\,(1-\xi)\Big)}{\delta\,(1+\xi)\,(1-\xi)^2 + 2\,\xi - 1}.$$

The numerator is clearly positive. The denominator is positive if and only if (11) holds.

We can now fully describe the Markov Perfect Equilibrium of the three-seller game, that is, the sellers' pricing strategies $p(i,j,k)$ and the buyer's adoption strategy $a(i,j,k)$:

$$p(1,1,i) \;=\; 0 \quad (i=0,1)$$

$$
\begin{aligned}
p(1,0,0) &= \begin{cases} \frac{u(1)-u(0)}{1-\delta(1-\xi)} & \text{if} \quad \gamma \leq \Phi(\delta,\xi) \\ \frac{u(1)}{1-\delta(1-\xi)^2} & \text{if} \quad \gamma > \Phi(\delta,\xi) \end{cases} \\
p(0,0,0) &= 0 \\
a(0,0,0) &= \begin{cases} N & \text{if} \quad \delta > \Gamma(\xi) \quad \text{and} \quad \gamma \geq \Psi(\delta,\xi) \\ Y & \text{otherwise} \end{cases} \\
a(i,j,k) &= Y \quad \text{if} \quad (i,j,k) \neq (0,0,0)
\end{aligned}
$$

where we've used the fact that $U(1) - U(0) = \frac{u(1)-u(0)}{1-\delta(1-\xi)}$. ■

Proof of Proposition 4: Waiting is efficient when the value from adopting today, $U(0)$, is less than the value from waiting, that is

$$U(0) < \delta \left((1-\xi)^3 U(0) + \left(1 - (1-\xi)^3\right) U(1) \right),$$

which is equivalent to

$$\gamma > \Theta(\delta,\xi) \equiv \frac{\left(1 - \delta(1-\xi)^3\right)}{\delta\xi(1-\xi)(2-\xi)}.$$

It can be shown that this condition is weaker than the condition for optimal waiting, that is, $\Psi(\delta,\xi) > \Theta(\delta,\xi)$. In fact, computation establishes that

$$\Psi(\delta,\xi) - \Theta(\delta,\xi) = \frac{3(1-\delta(1-\xi))\left(1-\delta(1-\xi)^3\right)}{\delta\xi\left(\delta(1+\xi)(1-\xi)^2 + 2\xi - 1\right)(2-\xi)}.$$

The numerator is clearly positive, while the denominator is positive if and only if $\delta > \Gamma(\xi)$. As a result, we conclude that there is excessive early adoption in equilibrium. ■

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