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 in the literature: 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, the buyer chooses the leading technology design as soon as the discounted payoff from doing so is positive. Early adoption occurs despite the fact there is an option value of waiting (and thus obtaining better information about the evolution of each technology design). 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 consider a variety of extensions that allow us to evaluate the robustness of our "early adoption" result.

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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. The existence of alternative designs leads to a variety of tradeoffs: a static one between the quality and price of these alternatives; and a dynamic one 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 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.

The case of wireless telecommunications provides an interesting illustration and may help setting the stage for our analysis. There are currently two main proprietary designs (CDMA2000, WCDMA), each somewhere between second a third generation (see Gandal et al., 2003); and a series of relevant technology users (equipment manufacturers, wireless communications operators). This and other examples clearly suggest that reality is far from the two-stage model (technology development, technology adoption) frequently assumed in economic analysis. When a user commits to one of the designs it commits to an uncertain stream of future benefits, which largely depend on the success of the technology owner (and other contributors) in improving that particular 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 potential buyers licensing terms; and (c) the potential buyer must decide when and which licensing terms to accept. We are interested in looking both at sellers' and 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 benefits 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. 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 sellers. In contrast with 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 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. In other words, 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. 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.

We thus have a situation where, somewhat paradoxically, price competition destroys value considerably; but additional competition may improve things. The reason is that additional competition means mainly more competition in the future, which in turn makes waiting a better option for the buyer, which in turn increases industry value.

We are not the first paper to show that inviting competition may increase value. For example, Farrell and Galini (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 buyers from 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.[1]

Our paper is also by no means the first to address strategic issues in the adoption of new technology. Important references include Reinganum (1981), Fudenberg and Tirole (1985), Riordan (1992). 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.[2] One 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.

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.[3]

[1]There is however a difference between our paper and the previous literature. Normally, an extra competitor is seen as a substitute for a seller's commitment to future prices. However, we show that a seller cannot improve its situation by unilaterally committing to future prices.

[2]There is also a literature on non-strategic aspects of optimal adoption on a new technology, including the seminal work by Jensen (1982). See Reinganum (1989) for an early survey of the literature and Hoppe (2002) for a more recent one. See also the survey by Geroski (2000), which emphasizes new technology diffusion.

[3]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

Our information framework is different from Lee (2003): we consider two stochastically independent competing technologies. Our Proposition 1, like Lee's (2003) central result, indicates there is no waiting in equilibrium; but for a different reason. In fact, in our model immediate adoption takes place even when waiting would lead to lower differentiation. The reason for our no-wait result is that any potential gains from waiting would be taken away by higher prices. To stress the importance of this effect, we consider the extension to three competing sellers and show that waiting may occur in equilibrium. In fact, with more than two competing sellers, there are events (simultaneous technology improvement by two lagging technologies) under which the buyer is able to capture the increase in benefits.

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 levels. Our analysis focuses on the buyer's decision. We extend the intuition of buyers' incentives to wait and show how this depends critically on the number of sellers.

The paper is structured as follows. Section 2 introduces the model. The results for the two-seller case are in Section 3, and the extension to three sellers is in Section 4. Section 5 discusses several other extensions and applications.

2 Model

Suppose there are two sellers, each offering an alternative design of a new technology, and one buyer. The value of each seller's technology design evolves stochastically over an infinite number of periods. Sellers must decide how to price their technology design at each stage of the process. 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. These are one-time license fees that entitle the buyer to the current and any future version of the technology design they choose. Next the buyer decides whether to adopt (buy one of the techology desings) or rather to wait. We assume adoption decisions are exclusive (one design at most) and irreversible. Finally, Nature determines

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.

the evolution of each of the technology designs according to an exogenously given, commonly known, stochastic process. Specifically, 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.

Until adoption takes place, the buyer receives zero payoff each period. Upon adoption, the buyer pays a license fee and receives a payoff flow of $\sum \delta^t u(\ell_t)$, where ℓ_t is the level, at time t, of the chosen technology design. Seller's payoffs are exclusively given by license fees received from the buyer.

We make a series of assumptions regarding the technology and licensing contracts. First, we assume that sellers cannot commit to future prices (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 $u(\ell) > 0,\ \ell = 0, 1$. Later in the paper we depart from these assumptions. We then show that the assumption regarding commitment to future prices is crucial for our results; whereas the remaining assumptions 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 $u(\ell) < 0$. In that case, we would denote by state 0 the first state such that $u(\ell) > 0$. In other words, our analysis should be understood as applying to the period of a technology design such that adoption benefits are positive.

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. The four states where the buyer has not opted for one of the technologies are characterized by (i, j), $i, j = 0, 1$, where i and j are the technology levels of designs A and B. The four states where the buyer has committed to a design are characterized by the design's name (A or B) and that design's technology level (0 or 1).

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

$U(i)$, where i is the technology level of the adopted design. We have

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

For simplicity, if with some abuse of notation, we will 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 is at j; and $V(i, j)$ the buyer's equilibrium value function.

3 Equilibrium

In this section, we solve for the Markov Perfect equilibrium of the game. 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

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

In fact, if neither design improves, the buyer gets $U(0)$. If only one design improves, 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

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

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.*[4] In 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 a design today the buyer gets $u(0)$ today plus $U(i')$ tomorrow. Since $U(i')$ is weakly greater than $\min\{U(i'), U(j')\}$ and $u(0)$ 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 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.** 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. Therefore, the question is 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

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

Notice the contrast with (1). Whereas in equilibrium the buyer only gains when *both* designs improve, from a social point of view it suffices that one of

[4] 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 the technology is profitable.

the designs improve. As a result, one can find parameter values such that the value in (3) is greater than $U(0)$ (the value in (2)), and waiting is socially optimal. Specifically, if

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

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.[5] Interestingly, $\Phi(\delta, \xi)$ is *not* monotonic in ξ. In fact, it can be shown that Φ is minimized for $\xi \in (0, \frac{1}{2})$.[6] 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's 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.

4 Three sellers

Consider now the case when 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

[5]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.

[6]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 $\delta \in (0, 1)$.

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 both laggards improve their design in the next period, in which case waiting would give the buyer a (weakly) 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 easily be 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 $U(1)$ 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.

5 Discussion

Our results for the two-seller case are quite stark: no matter how much buyer and sellers may have to gain from delaying the adoption decision, waiting never takes place in equilibrium. Since sellers cannot commit to future prices, all of the increase in surplus from waiting is captured by the successful seller (whose technology design improved faster). As a result, the buyer has no incentive to wait.

The situation is somewhat different when we consider three sellers instead of two. The reason is that there are states of the world when two technologies improve; and when that happens the surplus increase from waiting accrues to the buyer (through Bertrand competition). Notice that this does not always happen, so we may still obtain inefficient early adoption.

The externality underlying the inefficient adoption result is similar to the hold-up problem. Both sellers and buyer would be better off if the latter were to delay adoption. However, sellers are unable to commit not to extract the increased surplus resulting from the waiting decision. When there are more than two sellers, the possibility of future competition effectively creates a commitment not to extract the buyer's increased rent. This fact alleviates the "hold-up" problem, though it doesn't completely solve it.

Although we consider symmetric Bertrand price competition, our results suggest that there are important differences between the game played by two and the game played by three sellers. This contrasts with the static Bertrand game, where the "discontinuity" takes place as we go from one to two players. As mentioned above, the intuition is that, with three players, technology leaders can commit not to extract future surplus from the buyer. Related literature (e.g., Farrell and Galini, 1988) considers the possibility of attracting competitors as a way to commit not to increase future prices. Like ours, their problem has the nature of a hold-up game: the buyer must make an investment in order to use the seller's product, but once that investment is made it is in the seller's best interest to increase prices. In contrast to that literature, in our paper the value of committing to future competition is to provide incentives for the buyer to delay its adoption decision, not to make an investment now.

■ **Robustness and extensions.** Our main results are based on a fairly simple, stylized model. How important are our assumptions? In Section 2, we listed four basic assumptions: (a) sellers cannot commit to future prices; (b) the buyer chooses one technology design only; (c) the technology license entitles the buyer to all future versions of a given technology design; (d) each technology design evolves over two levels only. In the next paragraphs, we discuss the importance of each of these assumptions.

The assumption that sellers cannot commit to future prices is quite crucial to our results. In fact, could sellers commit to future prices, then the efficient solution would be obtained. Since total welfare is greater when the buyer waits, then there are gains from trade from waiting; that is, there are future prices such that both buyer and seller would be better off by waiting. However, *unilateral* commitment to future prices does not suffice to recover efficiency. To see this, consider the best case for waiting: in state (0,0), one of the sellers commits to keeping prices at zero even if it unilaterally improves its technology. Then a buyers expected benefit from waiting would be $\delta\,\Big(\xi\,U(1) + (1-\xi)\,U(0)\Big)$. But this is still lower than what the buyer would get from immediate adoption, $u(0) + \delta\,\Big(\xi\,U(1) + (1-\xi)\,U(0)\Big)$.

Even if sellers cannot commit to future prices, a tantalizing possibility is for a seller to *pay the buyer* (in the current period) for the latter to wait until at least the next period. However, we can show that the minimum a buyer would require in order to accept such offer is more than a seller would be willing to pay. Intuitively, there is an externality in this "bribing" process: by inducing the buyer to wait, a seller benefits the competing seller, who may end up being the chosen seller. Naturally, if sellers can "collude" and split the cost of bribing the buyer to wait, then waiting would take place. But if the sellers can effectively collude, then they might as well collude on higher prices in the present period, which would also induce the seller to wait. In fact, this is one instance where collusion on prices would be welfare increasing.[7]

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 cots of investing in a particular technology design. Our assumption would then be equivalent to the assumption that the fixed costs are very high.

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.

The assumption that there are only two steps in the technology ladder is not at all important. In fact, the intuition underlying Proposition 1 is quite general. Suppose the current technology state is (i, j) and that each technology evolves over n stages such that $u(i) > 0$ for all $i = 1, \ldots, n$. Given Bertrand competition, 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 (say i) 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.

To conclude, we consider two possible additional extensions. First, the case when the technology designs are horizontally differentiated, in addition to vertically differentiated. Clearly, if the degree of horizontal product differentiation is sufficiently large then our results won't necessarily hold. For example, a buyer might prefer a technology design at a lower stage of development. Notice however that our results are not "knife-edged," that is, they still hold if there is a little bit of horizontal product differentiation.

Throughout the paper, we assume that each buyer's payoff is independent of the other buyers' decisions. In fact, this assumption allows us to examine the decision problem of an individual, isolated buyer. Whenever payoffs are interdependent, the problem becomes significantly more complicated. For example, if there are significant network externalities, then one can easily find

[7]Bribing buyers to wait creates an additional problem (also found when setting negative prices), namely finding serious buyers (as opposed to buyers who simply want to collect the bribe).

multiple equilibria, some of which feature strategic waiting by buyers.

6 Conclusion

As acknowledged in the previous section, our analysis is simplistic in many respects. But simplicity has the advantage of highlighting one central point. Ours is that, in a dynamic context where technologies evolve stochastically and sellers attempt to attract technology adopters, price competition leads to inefficiently early adoption. It is well know that, in a static context, price competition destroys the seller's value;[8] but typically such lost value is captured by buyers. By contrast, in a dynamic context such as ours price competition leads to a loss of the total value captured by buyers and sellers.

The real world is far from the ideal of a two-stage model with R&D investment in the first period and price market in the second. In wireless telecommunications and many other examples competition for buyers gets under way well before the end of the development process. Our analysis suggests that the world would be a better place if firms could commit to play something closer to the two-stage model frequently used in economic analysis.

[8]See, for example, Cabral and Villas-Boas' (2005) characterization of Bertrand traps and supertraps.

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 leader's binding constraint is the buyer's option of purchasing from a laggard today. Then Bertrand competition implies $p(1,0,0)=U(1)-U(0)$ and the buyer's expected payoff from waiting is

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

Buying now from a laggard gives the buyer expected payoff

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

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

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

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 where 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

$$U(1)-p(1,0,0)=\delta\left((1-\xi)^2\left(U(1)-p(1,0,0)\right)+\left(1-(1-\xi)^2\right)U(1)\right),\quad(4)$$

which yields

$$p(1,0,0)=\frac{u(1)}{1-\delta(1-\xi)^2},\quad(5)$$

and an equilibrium value for the buyer of

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

Notice that, if $p(1,0,0) = 0$, then the left-hand side of (4) 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 (4) 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

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

The equilibrium hypothesis thus requires that

$$U(0) > \delta\left(\left((1-\xi)^3 + 3(1-\xi)^2\,\xi\right)U(0) + \left(3(1-\xi)\,\xi^2 + \xi^3\right)U(1)\right), \tag{7}$$

which is equivalent to

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

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 require condition becomes

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

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 (6). Make the equilibrium hypothesis that the buyer waits at state $(0,0,0)$. The value from waiting is given by the solution to

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

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

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

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

$$\delta > \Gamma(\xi) \equiv \frac{1-2\xi}{(1+\xi)(1-\xi)^2}. \tag{8}$$

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 (8) 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 $a(i,j,k)$:

$$\begin{aligned} p(1,1,i) &= 0 \quad (i=0,1) \\ p(1,0,0) &= \begin{cases} \frac{u(1)-u(0)}{1-\delta(1-\xi)} & \text{if} \quad \gamma \leq \Phi(\delta,\xi) \\ \frac{u(1)}{1-\delta(1-\xi)^2} & \text{if} \quad \gamma > \Phi(\delta,\xi) \end{cases} \end{aligned}$$

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

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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