Technology Adoption with Multiple Alternative Designs and the Option to Wait

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July 2004

Abstract

Frequently, new technologies arise under two or more alternative designs. Moreover, the state of each design evolves over time as a result of various cumulative improvements. In this paper, we study the strategic interaction between "incumbent" firms (those who already own a design) and "entrants" (those who do not but would like to adopt the new technology). We focus on two important decisions by an entrant: when to choose a design and which design to choose. We show that, in equilibrium, an entrant chooses the leading design and does not wait. While the former decision is efficient, the latter is generally not: the incumbent firms' inability to commit to future prices leads to inefficiently early technology adoption.

Keywords: technology standards, alliances.
JEL Code Nos.: L1, L5.

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1 Introduction

Frequently, new technologies arise under two or more alternative versions. Moreover, the state of each technology version evolves over time as a result of various cumulative improvements. For example, in the early stages of the VCR industry there were as many as thirty firms experimenting with various recording and playing formats.[1] Ultimately, two of these reached the market, those developed by Sony and JVC. Over the years Sony's Betamax and JVC's VHS gradually improved in quality, namely in terms of playing time, one of the more important quality features. Sony's Betamax improved from 1 hour playing time in 1975 to 5 hours in 1982, whereas JVC's VHS improved from 2 hours in 1976 to 8 hours in 1982.

When presented with multiple competing and evolving technology designs, firms face a number of important strategic decisions. The owners of each technology design would potentially like to attract as many firms as possible, thus increasing royalties and other benefits. In turn, for a firm that does not own a design the crucial decision is *which* design to adopt, and *when* to do so. To continue with the VCR example, shortly after JVC's introduction of the VHS format in September 1976, all major manufacturers in the Japanese market aligned with one of the two formats. By 1977, Sony's group included Toshiba and Sanyo, while JVC, by the end of 1976, had signed up Matsushita, Hitachi, Mitsubishi and Sharp.

In this paper, we study the strategic interaction between "incumbent" firms (those who already own a design and are willing to sell it) and "entrants" (those who do not but would like to adopt the new technology in one of the available formats). We assume that each technology design evolves stochastically over time, and that in each period the incumbent firms offer a potential entrant licensing terms. The entrant must decide when and which licensing terms to accept.

In our base case, we assume that there are two symmetric incumbents, i.e., two firms with identical but independent stochastic processes of technology evolution; and one potential entrant who (a) does not influence the advance of the design it licenses and (b) does not compete in the product market with the incumbents. We show that, in equilibrium, the entrant chooses the leading technology design. The intuition is that, as in Bertrand competition with vertical differentiation, the firm with a better product makes the sale. Moreover, the solution is socially efficient: a welfare maximizing planner would

[1]The following discussion of the VCR industry draws extensively on Cusumano, Mylonadis and Rosenbloom (1992), Grindley (1995), and Rohlfs (2001).

also pick the leading technology design.

Our second result is more surprising: we show that the entrant licenses one of the technology designs as soon as it is faced with the choice. Specifically, the entrant does not wait even if both designs are at their earliest levels of development. The idea is that any potential benefits from waiting and observing which technology design evolves faster are taken away in the form of higher licensing fees. Moreover, if players are patient enough then the solution is socially inefficient: a welfare maximizing planner would prefer the entrant to wait and then choose the leading technology design. Key to this result is our assumption that incumbents cannot offer contracts contingent on future technology improvements. In fact, if such contracts were available then the equilibrium solution would be socially efficient.

We consider several extensions of our basic framework. First, we generalize the model to the case when there are more than two incumbents. This extension is non-trivial. In fact, we show there are cases when the entrant waits (as social efficiency would dictate). The reason is that there is a chance that *two* incumbent designs 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 incumbents may imply equilibrium waiting, we show that the social optimum (weakly) implies longer waiting than in equilibrium (as in the case of two incumbents).

Our second extension is to consider an entrant who contributes to the development of the technology design it adopts.[2] Specifically, we consider the extreme case of an entrant who, like a pure research lab, does not directly benefit from the technology design it adopts but contributes to its development. We show that, in equilibrium, such a "research" entrant chooses the lagging technology design, the opposite of a pure "production" entrant, the case we initially considered. It is still true that an entrant will never wait, though in the "research entrant" extreme waiting would be socially inefficient.

Other extensions we consider include the possibility of the entrant having an idiosyncratic preference for one of the technology designs, asymmetric technology evolution functions, network effects, product market competition, and multiple entrants.

Our paper is by no means the first to address strategic issues in the adoption of new technology. Important references include Reinganum (1981), Fu-

[2]Matsushita, for instance, contributed significantly to the development of the VHS format: it was the first firm to develop a 4 hour and a 6 hour tape.

denberg 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.[3] 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) is closest to our work. Like us, he 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]

Our information framework is different from Lee (2003): we consider two stochastically independent competing technologies. Our Proposition 2, 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 fees. 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

[3]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.

[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.

is able to capture the increase in benefits.

The paper is structured as follows. Section 2 introduces the model. We derive the results regarding the choice of technology design in Section 3, and the timing of choice in Sections 4 and 3. In Section 6 we introduce a special case with only two technology levels. The extension to more than two incumbent firms is derived in Section 7. In Section 9, we consider several other extensions and potential areas for future research. Section 10 concludes the paper.

2 Model

Suppose there are two existing technology designs, each owned by a different firm. A third firm, unable or unwilling to develop its own design, wants to license one of the existing designs. The game proceeds over an infinite number of periods. Each period is divided into two stages: a licensing stage and a research stage. At the licensing stage, if the entrant has not chosen a technology design in a previous period, then the two incumbent firms simultaneously submit license fees. If the entrant decides to join one of the incumbents, then it pays a license fee, which we assume is a one-time payment. At the research stage, Nature draws values of technological capability for each of the technology designs. These values are drawn from the set $\{0, 1, ..., m\}$ according to c.d.f. $F(x)$ (density f). An improvement in technology i takes place if the value drawn by Nature for that technology is better than the existing one.

The state of the game is given by each technology's current level as well as the entrant's status (adopted technology design x, adopted technology design y, has not made a decision yet). The initial technology levels are given.

Finally, payoffs are as follows. In each period, a firm that owns or licenses the technology earns a payoff $u(x)$, a strictly increasing, concave function, where x is the current state of the particular technology design the firm uses.

Given this specification, we can now derive value functions recursively. Let $S(x)$ be the value of an incumbent firm *excluding* license fees. We have

$$\begin{aligned} S(x) &= u(x) + \delta \left(F(x)S(x) + \sum_{x+1}^{m} f(t)S(t) \right) \\ &= \frac{u(x)}{1 - \delta F(x)} + \frac{\delta \sum_{x+1}^{m} f(t)S(t)}{1 - \delta F(x)} \end{aligned}$$

Simple calculations show that this is an increasing function:

Lemma 1 *$S(x)$ is strictly increasing.*

Table 1: Model Notation.

x	current state of technology x; $x \in \{0, ..., m\}$;
s	state of the game: $s = (x, y, ..., z)$.
$S(x)$	discounted expected value of a technology when developed by one research unit only;
$A(x)$	discounted expected value of a technology when developed by two research units (alliance);
$F(x)$	c.d.f. of R&D random draws for a solo research concern;
$G(x)$	c.d.f. of R&D random draws for an R&D alliance;
$p(x)$	license fee offered by incumbent x in state s;
$u(x)$	production payoff from technology at level x;
δ	discount factor;
ξ	$f(1)$ in the special case when $m = 1$.

There are two questions of interest: First, which of the two available designs should the entrant favor; second, when should the entrant make a decision. In the next two sections, we consider these questions in turn.

3 Choice of technology design

Intuitively, one would expect that it is better to join a leading rather than a lagging technology design. Given our assumption that both firms draw technology levels from the same distribution, the expected future payoffs stemming from the leading technology design are greater. We conclude that

Proposition 1 *In equilibrium, the entrant chooses the leading technology design.*

Proof: Suppose that the entrant is to make a choice at time t. Incumbents have nothing to gain from an entrant other then license fees. From the entrant's point of view, the value of choosing a design that is currently at level x is given by $S(x)$. Since $S(.)$ is increasing (Lemma 1), it follows that the firm with technology level $y > x$ will attract the entrant by charging a fee $S(y) - S(x)$. In equilibrium the leader ends up with a value of $2S(y) - S(x)$, while both the laggard and the entrant will have a value of $S(x)$. ■

The thrust of the proof is to note that the game is roughly analogous to Bertrand competition with zero marginal cost levels and different valuations.

In equilibrium, it's the firm with a higher valuation that makes the sale, setting a price equal to the difference in valuations.

4 Timing of technology adoption

Consider now the second question: when should an entrant join one of the incumbent technology designs? We find that,

Proposition 2 *In equilibrium, the entrant joins an incumbent at the earliest feasible date.*

Proof: Suppose that, for all values (x'', y'') *not* in the set S, defined by $x' \leq x$ and $y' \leq y$, waiting is not an equilibrium. Suppose that waiting is an equilibrium at (x, y), where $x \leq y$ (without loss of generality). Then, it must be the case that no incumbent can propose to the entrant a better deal than waiting.

Let $J(x, y)$ be the joint value that incumbent y and the entrant expect to get if the entrant decides to wait at (x, y) for one period but joins in the next period even if the state does not change.[5] We then have

$$\begin{aligned} J(x,y) &= u(y) + \delta \Bigg(F(x)F(y)2S(y) + F(y)\Big(1 - F(x)\Big)2S(y) + \\ &\qquad + \sum_{i=y+1}^{m} f(i)2S(i) \Bigg) \end{aligned}$$

The three terms after δ on the right hand side of this equation correspond to the following cases: (a) neither incumbent improves its technology design, in which case we remain in the same state; (b) the lagging technology design improves, whereas the leading technology design does not; (c) both technology designs improve. The payoff in case (a) is justified by our assumption that the entrant's strategy is to join in the next period, regardless of the state. Cases (b) and (c) require some additional explanation. Suppose the new state is given by (x'', y''). Two subcases are possible. If $x'' > \max(y, y'')$ then the entrant will form an alliance with incumbent x. However, the entrant pays a license fee equal to $S(x'') - S\Big(\max(y, y'')\Big)$ and will be left with $S\Big(\max(y, y'')\Big)$. Hence, the joint payoff of entrant and incumbent will be $2S\Big(\max(y, y'')\Big)$. If

[5] By the one-stage-deviation principle (cf Fudenberg and Tirole, 1994) it suffices to consider a one-time deviation from the prescribed equilibrium strategy in order to confirm that it is indeed an equilibrium strategy.

$x'' < \max(y, y'')$, then the entrant will form an alliance with incumbent y and their joint payoff will be again $2S\Big(\max(y, y'')\Big)$. Consequently, regardless of which incumbent will be the leader in any future state, the joint payoff of the entrant and incumbent y will be $2S\Big(\max(y, y'')\Big)$.

By immediately joining incumbent y, the entrant and the incumbent jointly make $2S(y)$. Given our definition of $S(y)$ and $J(x, y)$ it follows that:

$$2S(y) - J(x, y) = u(y) > 0,$$

which contradicts the equilibrium hypothesis. Now consider state $(x-1, y)$. The only states that can be reached from here, in addition to state $(x-1, y)$ itself, are (x, y) and states (x'', y'') outside of S. The above argument can be applied, implying no waiting at $(x-1, y)$. By induction, we conclude that there is no waiting at any state such that $x' = x$ *or* $y' = y$. We have thus gone from an initial set $S = \{(x', y') \text{ s.t. } x' \leq x, y' \leq y\}$ to a new set $S = \{(x', y') \text{ s.t. } x' \leq x-1, y' \leq y-1\}$. Clearly, there is no waiting when S coincides with the entire set. By induction, we conclude there is no waiting at any state. ■

It is worthwhile emphasizing the intuition for this result. If the entrant's strategy is to wait for one period and then join regardless of the state, the joint future payoff of entrant and incumbent y (the current leader) is always $2S\Big(\max(y, y'')\Big)$, regardless of whether incumbent y remains a leader or becomes a follower. The reason is that even though incumbent y may become a follower, in which case the entrant joins the new leader, the entrant's value is still equal to $S\Big(\max(y, y'')\Big)$ since it has to pay the new leader a higher equilibrium license fee. As a result, in the case of waiting, the joint payoff of the entrant and incumbent y depends only on incumbent y's expected technology improvement. But so does the joint payoff from adopting in the current period. Hence, adopting today rather than tomorrow adds the extra payoff $u(y)$ from production today.

One might expect the entrant to have some value from waiting, at least in some circumstances. For example, if the two incumbents are still at low technology levels, by waiting, one might get information about their rate of success. Moreover, if one firm is ahead of the other, waiting might have the advantage of bringing the firms together, thus allowing the entrant to play one against the other. Proposition 2 shows that none of these considerations applies in the present context. The reason is that all of the entrant's potential gains from waiting are taken away by Bertrand competition.

5 Social welfare

In the previous sections, we looked at the equilibrium solution. How does this differ from the social optimum? A central planner would choose time and technology design so as to maximize the incremental welfare brought about by the entrant. Our main result in this section shows that, starting from state (x, y), where $x < y$, a social planner may prefer to wait.

Proposition 3 *There exists a* $\overline{u}\,(y;\xi,\delta)$ *such that, if* $u\,(y) < \overline{u}\,(y;\xi,\delta)$*, then it is socially optimal for the entrant to wait when in state* (x, y)*, where* $x < y$*.*

Proof: Suppose we are currently in state (x, y). Consider the increase in social welfare brought about by the entrant. If the entrant chooses technology design y now, then the discounted expected benefit is

$$S(y) = u(y) + \delta \left(F(y)S(y) + \sum_{y+1}^{m} f(t)S(t) \right)$$

If the entrant decides to wait for one period instead, then the payoff is analogous to $S(y)$ with a progress function given by $G(y) = F(y)^2$. The idea is that, by waiting, the entrant has the option to choose the best technology design in the next period out of two possible technology designs. Since $G(y)$ first-order stochastically dominates $F(y)$, and $S(y)$ is strictly increasing (cf Lemma 1), it follows that, except for current payoff $u(y)$, the expected payoff from waiting is strictly greater than choosing now (cf Milgrom, 1981). ■

The intuition is straightforward. Suppose we ignore license fees, as social optimization prescribes. Suppose moreover that current payoff is zero. Then waiting is the optimal strategy. Making a choice now would lead, with positive probability, to regret tomorrow.

6 The $m = 1$ case

We now consider the special case when $m = 1$, that is, when the technology level x can be at one of two possible levels: 0 and 1. We maintain this assumption throughout the remainder of the paper (unless otherwise stated). Moreover, we let $\xi \equiv f(1)$. This special case is useful in several ways. In this section, we consider the $m = 1$ case to better understand the intuition underlying Proposition 2.

Suppose the current state is $(0, 1)$. Given Bertrand competition between incumbents, the laggard reduces its license fee down to marginal cost (zero).

In equilibrium, the entrant is indifferent between joining either of the two incumbents. This implies that, if the entrant were to choose one of the designs now, it would receive a payoff equivalent to joining the laggard for free, that is, $S(0)$. This value is recursively derived as follows:

$$S(0) = u(0) + \delta \Big((1 - \xi) S(0) + \xi S(1) \Big) .$$

Suppose alternatively that the entrant decides to wait one period (and then continues the policy of not waiting). Then the entrant's expected payoff is:

$$W_E(0, 1) = 0 + \delta \Big((1 - \xi) S(0) + \xi S(1) \Big) ,$$

which is clearly lower than $S(0)$. Specifically, $W_E(0,1) = S(0) - u(0)$. In words, by waiting for one period, the entrant forgoes one period of production profits and gains nothing. Why is this so? There are two possible outcomes of the current period's uncertain R&D process: either the lagging technology design improves or it does not. If the lagging technology design does not improve, then we are back in the initial situation, and nothing is gained (in terms of future value) from waiting. If the lagging technology design improves from 0 to 1, then the entrant earns $S(1)$ from tomorrow on. In fact, there will be two incumbents with high-level of technology; Bertrand competition thus implies a zero license fee and the entrant captures the entire value $S(1)$. But this is exactly what the entrant would have gotten in expectation, had he not waited. So, in terms of future value, regardless of the outcome of today's R&D draw, the entrant is equally well off by adopting now as by waiting for one period. The only difference is then the current payoff flow $u(0)$ that is foregone by waiting.

7 Extension: three or more incumbents

Our results in the previous sections depend on a number of simplifying assumptions. In particular, Proposition 2 (no waiting) depends crucially on the assumption that there are only two incumbent firms, that is, two available technology designs. To see why, consider the case of three incumbents. Suppose we are currently in state $(0, 0, 1)$ and that the same reasoning applies as in the two-incumbent case (Section 4). Then, in equilibrium the entrant will be indifferent between joining either of the three incumbents. This implies that, if the entrant were to choose one of the technology designs now, it would receive a payoff equivalent to joining one of the laggards for free, that is, $S\,(0)$. The latter is recursively derived as follows:

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

Suppose alternatively that the entrant decides to wait one period (and then continues the policy of not waiting). Then the entrant's expected payoff is

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

While in the two-incumbents case it was clear that $S(0) > W_E(0,1)$, it is now quite possible that $S(0) < W_E(0,0,1)$. In fact, for any $\xi \in (0,1)$, $\delta \in (0,1)$, we can find a small enough $u(0)$ such that waiting is optimal.

The intuition is that, with two lagging technology desings, there are outcomes of today's R&D process that would lead the entrant to regret having made an early choice. Specifically, if the entrant joins the leader it receives a payoff of $S(0)$; whereas by waiting, the entrant could benefit from Bertrand competition between the leading technology design and *either one* of the now co-leading technology designs, yielding a payoff $S(1)$. With two incumbents, the entrant's expectation of getting a payoff $S(1)$ from waiting depends only on the improvement of the lagging technology design. However, the payoff from joining now, $S(0)$, already incorporates that possibility. With three incumbents, the likelihood of getting $S(1)$ by waiting is increased, since now there are two firms that can improve their technology designs. The payoff from joining now, $S(0)$, incorporates only the likelihood of one technology designs improving (which is clearly smaller than the likelihood of one out of two technology designs improving).

If $S(0) < W_E(0,0,1)$, then our equilibrium assumption that, at stage $(0,0,1)$, Bertrand competition leads the leader to set a fee $S(1) - S(0)$ is no longer valid. In fact, the leader's binding constraint is not competition from current laggards; rather, it is competition from the entrant's waiting option. The equilibrium fee would then be the one that makes the entrant just indifferent between waiting and not waiting: $p(0,0,1) = S(1) - W_E(0,0,1)$. This implies that, in equilibrium, and starting from state $(0,0,1)$, the entrant expects a value greater than $S(0)$.

We can now roll back to state $(0,0,0)$ to show that there can be waiting in equilibrium.

Proposition 4 *Suppose there are three incumbents and that $\xi > \frac{1}{2}$. There exists a $\overline{u}(\xi,\delta)$ such that, if $u(0) < \overline{u}(\xi,\delta)$, then in equilibrium and in state $(0,0,0)$ the entrant decides to wait.*

Proof: By moving ahead at state $(0,0,0)$, the entrant gets $S(0)$, computed as above, whereas by waiting it gets

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

Since $V_E(i,j,k) \geq S(0)$ and $V_E(0,0,1) > S(0)$, it follows that

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

If $u(0) = 0$, then both $S(0)$ and $W_E(0,0,0)$ are convex combinations of $S(0)$ and $S(1)$. Since $S(1) > S(0)$, it follows that $W_E(0,0,0) > S(0)$ if $\xi^2(3-2\,\xi) > \xi$, which is equivalent to $\xi > \frac{1}{2}$. We conclude that, if $\xi > \frac{1}{2}$, the expression following δ in $W_E(0,0,0)$ is greater than the corresponding expression in $S(0)$. Consequently, one can find a small enough $u(0)$ such that waiting is the equilibrium outcome. ■

Note that the conditions in Proposition 4 are sufficient, not necessary. We finally show that, while there may be waiting in equilibrium, it is still the case that the social optimum implies (weakly) waiting for longer than the equilibrium solutions.

Proposition 5 *The socially optimal time of adoption is never earlier than the equilibrium time of adoption.*

Proof: Suppose that

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

If this condition holds, then there is no waiting in state $(0,0,1)$ and in equilibrium $V(0,0,1) = S(0)$. It follows that, in equilibrium, there is no waiting in state (0,0,0) either.

Suppose now that

$$S(0) < \delta\left((1-\xi)^2 S(0) + \left(1-(1-\xi)^2\right)S(1)\right).$$

From the above discussion in the text, this may lead to waiting in equilibrium. However, since $S(1) > S(0)$, the above inequality implies that

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

which in turn implies that it is socially efficient to wait. ■

Proposition 5 is fairly intuitive. From a private point of view, the event that justifies waiting is the simultaneous technology improvement by two or more incumbents. From a social point of view, however, waiting pays off if at least one incumbent improves its technology design. As a result, equilibrium waiting is a sufficient condition for efficient waiting.

8 Extension: research alliances

Our second extension is to consider an entrant who contributes to the development of the technology design it adopts. For example, Matsushita, one of the "entrants" in the VCR race, contributed significantly to the development of the VHS format: it was the first firm to develop a 4 hour and a 6 hour tape. Specifically, we consider the extreme case of an entrant who, like a pure research lab, does not directly benefit from the technology design it adopts but contributes to its development.

We continue to consider the same timing as before. However, we now assume that a technology design adopted by an entrant progresses according to a distribution $G(x)$ that strictly dominates $F(x)$ in the sense of first-order stochastic dominance, that is, $G(x) < F(x)$ for all $x < m$. Finally, incumbent payoffs are as before, $u(s)$ per period, whereas, consistently with our assumption of a "pure research" entrant, the latter receives no "production" payoffs $u(s)$. In other words, the only payoff received by the entrant is the one-time payment by the incumbent firm it joins.

Let $A(x)$ be the incumbent's value, net of transfers to the entrant, given that it managed to attract the latter. We have

$$\begin{aligned} A(x) &= u(x) + \delta \left(G(x)S(x) + \sum_{x+1}^{m} g(t)S(t) \right) \\ &= \frac{u(x)}{1 - \delta G(x)} + \frac{\delta \sum_{x+1}^{m} g(t)S(t)}{1 - \delta G(x)}. \end{aligned}$$

Clearly, if the incumbent does not attract the entrant than its value is given by $S(x)$ (introduced in Section 2).

As before, there are two questions of interest: which of the two available designs should the entrant favor; and when should the entrant make a decision. Before considering these questions we establish a useful result, the proof of which can be found in the Appendix:

Lemma 2 *$A(x) - S(x)$ is strictly decreasing.*

We will now show that, in terms of choice of technology design, the equilibrium prediction in the R&D entrant case is the opposite of a pure production entrant.

Proposition 6 *In equilibrium, a pure research entrant chooses the lagging technology.*

Proof: Other than monetary transfers, a pure research entrant is indifferent between incumbents. The opposite is true for an incumbent, who has to gain from a pure research entrant insofar as a technology alliance speeds up the process of technology improvement. The entrant will thus chose the incumbent offering the most. Since $A - S$ is decreasing (Lemma 2), it follows that the firm with technology level $x < y$ will attract the entrant by paying $A(y) - S(y)$. In equilibrium, the laggard ends up with a value of $A(x) - \big(A(y) - S(y)\big)$, the leader with $S(y)$ and the entrant with $A(y) - S(y)$. ■

The thrust of the proof is to note that the game is analogous to a second price auction with different valuations. In equilibrium, the firm with higher valuation will make the purchase and pay a price equal to the other firm's valuation.

We proceed with the question regarding the timing of choice. Similarly to a production entrant we find that:

Proposition 7 *In equilibrium, a research entrant joins an incumbent at the earliest possible date, regardless of the number of incumbents.*

Proof: The added value that incumbent x and the entrant expect to get if the entrant decides to wait at (x, y) for one period but joins in the next period even if the state doesn't change is given by

$$J(x,y) = \delta \Bigg(F(x)F(y)\big(A(x) - S(x)\big) + F(x)\big(1 - F(y)\big)\big(A(x) - S(x)\big) + + \sum_{i=x+1}^{m} f(i)\big(A(x) - S(x)\big)\Bigg)$$

The three terms after δ on the right hand side of this equation correspond to the same cases as a production entrant. The payoff in case (a) is justified by our assumption that the entrant's strategy is to join in the next period, regardless of the state. For cases (b) and (c), again, two subcases are possible. Suppose the new state is given by (x'', y''). If $x'' < \max(y, y'')$, then the entrant will form an alliance with incumbent x, for an added value of $A(x'') - S(x'')$. If $x'' > \max(y, y'')$, then the entrant will form an alliance with incumbent y and receive a payoff of $A(x'') - S(x'')$, the added value of the entrant to a pairing with incumbent x. Consequently, regardless of which incumbent will be the laggard in any future state, the value added by the research entrant when pairing with incumbent x will be $A\left(\min(x, x'')\right) - S\left(\min(x, x'')\right)$.

By immediately joining incumbent x, the added value will simply be $A(x) - S(x)$. Given our definition of $A(x)$, $S(x)$ and $J(x, y)$ and using Lemma 2 it follows that

$$\left(A(x) - S(x)\right) - J(x, y) \geq (1 - \delta)\left(A(x) - S(x)\right) > 0,$$

which contradicts our equilibrium hypothesis. The argument then continues as in the case of a production entrant. ■

9 Other extensions

There are a number of other possible extensions to our framework. For example, if the two technology designs are sufficiently differentiated in the eyes of an entrant, then it is possible for a lagging standard to be chosen by a "production" entrant (cf Proposition 1) or a leading standard by a research entrant (cf Proposition 6). Along similar lines, if $u(x) < 0$ for some values of x then it is possible for an entrant to wait in equilibrium. The statement of Proposition 1, "the entrant joins an incumbent at the earliest feasible date," should then be read "the entrant joins the leading incumbent as soon as $u(x) > 0$."

Throughout the paper we have assumed that the value of a given technology x depends only on the state of that technology. More generally, we could think of payoff functions $u(s)$ that are a function of the entire state description, not just the level of technology x. Consider for example the case $m = 1$ and suppose that

$$u(0, 1) < u(0, 0) < u(1, 1) < u(1, 0),$$

which is consistent with the two incumbents competing in the product market or, alternatively, with there being strong network effects leading to a winner-take-all or winner-take-most "race" between the incumbents. In this setting, it is quite possible that Proposition 6 be violated, with a "research" entrant choosing to sign up with a leading (or winning) incumbent.[6]

It might be interesting to consider the case when there are n entrants. If these are "production" entrants, then Proposition 1 goes through: all entrants prefer to join the leading technology. The same is not true of Proposition 6. Suppose that an "alliance" of n firms (incumbent and $n-1$ "research" entrants) improves its technology design from draws from a distribution $F_n(x)$, where n is the number of research-oriented alliance members. Then if a sufficiently large number of firms join the laggard, it is possible that the leader's marginal value from attracting the next entrant be greater than the laggard's. In fact, starting from a state where incumbents are level, we would expect the entrants to split between the incumbents.

We have assumed that technology levels are drawn from a well know distribution $F(x)$. Consider the following more general model of R&D uncertainty. Suppose that incumbent i draws new technology levels from a distribution $F_i(x)$. Suppose moreover that $F_i(x)$ is randomly drawn from a set of distribution functions $\mathcal{F} = \{F_i(x)\}$; incumbents and entrants hold a common prior on each element of $\mathcal{F}$; and there is no asymmetric information. It can be shown that Proposition 2 still holds in this context. The idea is that, although value functions are more complicated, the fact that there is common knowledge regarding the future implies that Bertrand competition washes away any benefit from waiting.

10 Concluding remarks

The basic problem that we set out to address in this paper—choice among alternative versions of a new technology—is clearly relevant in many industries. As we look into specific real-world cases, we see that each case has its own specificities. Still, we believe that the results we derive can help understand the main forces at work. In Section 1, we mentioned the case of video cassette recorders (VCRs). Another interesting case is that of third-generation wireless telecommunications standards (see Gandal et al., 2003). Although opinions diverge, one may argue that Qualcomm's CDMA2000 is ahead of the 3G race against Nokia's WCDMA. Partly, this is due to the fact that CDMA2000 is a relatively simple upgrade with respect to existing CDMA, whereas WCDMA is a more drastic change. This implies a greater difficulty in bringing WCDMA to market, a fact that is reflected in the numbers: by the beginning of 2003,

[6] This is reminiscent of the "efficiency" or "joint profit" effect characterized by Gilbert and Newbery (1982) and others.

CDMA had signed up almost 32 million subscribers worldwide, compared to 160 thousand for WCDMA (Gandal et al, 2003). In this context, the results from Sections 3 and 8 suggest that research intensive firms are more likely to join the Nokia bandwagon, whereas production intensive firms are more likely to join the Qualcomm camp.

Appendix

Proof of Lemma 2: We first show that

$$\begin{aligned}
\Delta S &= S(x+1) - S(x) = \frac{\Delta u}{1-\delta F(x)} > 0 \\
\Delta A &= A(x+1) - A(x) = \frac{\Delta u}{1-\delta G(x)} > 0,
\end{aligned}$$

where $\Delta u = u(x+1) - u(x)$. In fact,

$$\begin{aligned}
S(x) &= u(x) + \delta\left(F(x)S(x) + \sum_{x+1}^{m} f(t)S(t)\,dt\right) \\
&= u(x) + \delta\left(F(x)S(x) + f(x+1)S(x+1)\sum_{x+2}^{m} f(t)S(t)\,dt\right) \\
&= u(x) + \delta\Bigg(F(x)S(x) - F(x)S(x+1) + F(x)S(x+1) + \\
&\qquad + f(x+1)S(x+1)\sum_{x+2}^{m} f(t)S(t)\,dt\Bigg) \\
&= u(x) + \delta\left(F(x)S(x) - F(x)S(x+1) + F(x+1)S(x+1)\sum_{x+2}^{m} f(t)S(t)\,dt\right)
\end{aligned}$$

Moreover,

$$S(x+1) = u(x+1) + \delta\left(F(x+1)S(x+1) + \sum_{x+2}^{m} f(t)S(t)\,dt\right)$$

It follows that

$$\Delta S(x) \equiv S(x+1) - S(x) = \Delta u(x) + \delta F(x)\Delta S(x),$$

or simply

$$\Delta S(x) = \frac{\Delta u(x)}{1-\delta F(x)}.$$

Similarly, we can show that

$$\Delta A(x) \equiv A(x+1) - A(x) = \frac{\Delta u(x)}{1-\delta G(x)}.$$

We therefore conclude that

$$\Big(A(x+1) - S(x+1)\Big) - \Big(A(x) - S(x)\Big) =$$
$$= \Delta A(x) - \Delta S(x) = \frac{\Delta u(x)}{1-\delta G(x)} - \frac{\Delta u(x)}{1-\delta F(x)} < 0,$$

since $F(x) > G(x)$ for all x. ■

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