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Second-mover advantages in the strategic adoption of new technology under uncertainty

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Abstract

This paper introduces technological uncertainty into a timing game of new technology adoption. It is shown that the timing neither necessarily involves first-mover advantages in precommitment equilibria (Reinganum, Review of Economic Studies, XLVIII (1981) 395–405) nor rent-equalization due to the threat of preemption (Fudenberg and Tirole, Review of Economic Studies, LII (1985) 383–401). Rather, there may be second-mover advantages because of informational spillovers. Furthermore, the model predicts that the equilibrium payoffs will typically be discontinuous and non-monotonic in the probability that the new technology is profitable. A welfare analysis reveals several market failures, and suggests that policy intervention should adequately depend on the nature of uncertainty and the rate of technological progress.

Keywords: Innovation; Timing; Technological uncertainty

JEL classification: L13; O31; O32

1. Introduction

Innovations are an important factor of industry performance. Economists have duly paid much attention to the analysis of new technology adoption (see Reinganum (1989) and Karshenas and Stoneman (1995), for comprehensive surveys). Most studies in this field tend to focus on identifying the factors that influence the timing of adoption. Surprisingly, the impact of adoption timing on firm performance and welfare has received scant attention in the literature.

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In an oligopoly, the adoption of new technology may endow the firm that adopts first with a competitive advantage. By reducing unit cost or introducing a better product, the first adopter is expected to enhance its market share. Being first, however, can involve high cost and uncertainty. The purpose of this paper is to explore a duopoly model of new technology adoption in which second-mover advantages accrue from uncertainty and decreasing adoption cost over time. The framework is used to identify several sources of market failure that justify policy intervention in the process of new technology adoption.

The model synthesizes and generalizes earlier approaches on the timing of new technology adoption. This is accomplished by integrating uncertainty regarding the profitability of an innovation into the timing game of Fudenberg and Tirole (1985), which in turn extends the Reinganum (1981) model. Reinganum shows that, for an innovation that is known to be profitable, there is a unique (modulo relabelling of firms) open-loop Nash equilibrium, which involves a first-mover advantage. By changing the information structure of the game from infinite information lags (open-loop) to negligible lags (closed-loop), Fudenberg and Tirole obtain a fundamentally different result: in the subgame-perfect equilibrium, any first-mover advantage is completely dissipated by preemptive adoption. The seminal contribution on adoption timing under uncertainty is the decision-theoretic model by Jensen (1982), in which firms gather information that can reduce the uncertainty about the value of an innovation. This value is represented by a parameter that can take one of two values such that adoption is either profitable or unprofitable. Jensen (1992a) considers a game-theoretic model of new technology adoption under uncertainty. However, the setting is a static one. The present paper follows Jensen in assuming that the innovation can either succeed or fail.

Technological uncertainty has been prominently introduced into a duopoly model of innovation by Reinganum (1983). She studies the Gilbert and Newbery (1982) model on innovation and the persistence of monopoly in the context of a stochastic innovative process, and demonstrates that the qualitative properties of equilibrium behaviour are particularly sensitive to the presence or absence of uncertainty.

In the present paper, the introduction of uncertainty about the profitability of the innovation yields the possibility of second-mover advantages in equilibrium. Once a firm adopts the new technology and thereby reveals its true value, the rival firm will be able to revise its adoption decision based on the knowledge as to whether adoption will be profitable or not. This in turn will create the basis for a second-mover advantage due to the irreversibility of investment. However, because of strategic interaction in the product market, a firm's gain in profits from adoption is decreasing in the number of previous adopters. This generates the basis for a first-mover advantage to adoption. While any potential first-mover advantage is completely dissipated in equilibrium if firms are unable to precommit to future actions (see Fudenberg and Tirole, 1985), a potential second-mover advantage may prevail as the closed-loop equilibrium outcome. This paper shows that the closed-loop equilibrium entails payoff-equalization due to the threat of preemption if the probability of success is high, and a second-mover advantage because of informational spillovers if the probability is low.

The analysis reveals a discontinuity and non-monotonicity of the equilibrium payoffs in the probability that the new technology is profitable. A small increase in the probability of success can convert the competition from a waiting game to a preemption game, and thereby cause a downwards jump in the equilibrium payoffs of both firms. The reason is that preemptive adoption behaviour results in excessive rent-dissipation.

This paper also explores normative issues of adoption timing under uncertainty. It is shown that equilibrium adoption behaviour tends to diverge from the social optimum for four reasons. First, preemption may hasten adoption inefficiently (the preemption effect). Second, adoption by one firm may hurt its rival due to increased competition in the product market (the business-stealing effect). Third, because of informational spillovers the first adoption may be delayed inefficiently (the informational-spillover effect). And fourth, expected consumer surplus is maximized when both firms adopt immediately, whereas firms' profits are not (the consumer-surplus effect). Policy recommendations should thus take the relative strengths of these four arguments into account. One perhaps striking point that the welfare results suggest is that policies aimed at increasing the general speed of adoption (i.e. inducing both firms to adopt earlier) are not always desirable in the case of a waiting game, nor are policies aimed at decreasing this speed (i.e. inducing both firms to adopt later) always appropriate in the case of a preemption game. Rather, social welfare may be increased by an earlier initial and a later follow-on adoption. The reason is that the consumer-surplus effect from a follow-on adoption is outweighed by the business-stealing effect in a waiting game that is likely to involve spacing of adoption between firms, and that the preemption effect is not strong enough to dominate the other countervailing effects in a preemption game in which the rate of technological progress is sufficiently low.

The recent theoretical literature on the timing of new technology adoption tends to focus either solely on preemption games due to rivalry in the product market (e.g. Riordan, 1992), or on waiting games due to technological uncertainty and informational spillovers (e.g. Mariotti, 1992; Kapur, 1995). These two strands are unified in the present paper. That technological competition may take the form of a race or a waiting game has been emphasized by Katz and Shapiro (1987) and Dasgupta (1988) in the context of R&D. Both papers, in contrast to the present one, assume that the game ends as soon as one firm innovates, i.e. receives a patent that may or may not prevent the rival firm from free-riding. Moreover, their studies focus on the effects of potential first-mover and second-mover advantages on the innovator's R&D incentive, while the present paper looks for the preconditions of second-mover advantages in equilibrium. Dutta et al. (1995) consider preemption and waiting in the context of new market entry. In their paper, the critical factor is the strategic advantage from developing a high-quality product innovation and not uncertainty surrounding the profitability of the innovation. Choi (1998) finds that a change in the degree of patent protection may convert the entry timing of potential imitators from a preemption game to one of waiting. The reason is that, depending on the strength of the intellectual property rights, a patent-holder will either accommodate initial entry or encounter it with an infringement suit which can reveal information regarding the validity of the patent to other firms.

As part of his patent-licensing analysis, Jensen (1992b) examines a two-stage adoption game. He notes that this is a preemption game for high probabilities of success and a waiting game for low probabilities of success which matters in determining the optimal licensing strategy. The present paper provides an extension of Jensen's (1992b) results to the case of an infinite-horizon, continuous-time framework in which the strategic timing of adoption is a critical factor. Finally, Hendricks (1992) discusses, but in contrast to the present paper, does not formally derive the possibility of second-mover advantages to adoption. The primary focus of his analysis is on ex-post first-mover advantages in the Fudenberg and Tirole model due to uncertainty about the innovative capabilities of the rival firm.

In the empirical literature, the question of whether there are first-mover or second-mover advantages in the introduction of a new product has received much attention. In a recent study, Tellis and Golder (1996) discover that the failure rate for pioneers is high: almost half do not survive. In contrast to earlier studies, Tellis and Golder include all the pioneer companies and brands that failed in the sample, and find little evidence in support of the well-known principle in business theory and practice of being first to market. Their results rather suggest that following can be better than pioneering.

Section 2 presents the model. The closed-loop equilibrium behaviour is analyzed in Section 3. Section 4 discusses welfare effects. Section 5 concludes. All proofs are placed in Appendix A.

2. The model

There are two firms ($i = 1,2$) initially having equilibrium profit flows of Π_0. An innovation becomes available at date 0. Following Jensen (1982), the value of the innovation is stochastic in the sense that the innovation is 'good' (i.e. it increases profits) with probability p, and 'bad' (i.e. it does not increase profits) with probability $(1 - p)$. p is common knowledge. With the first adoption, the nature of the innovation is publicly known. Thus, a firm's adoption gives rise to an informational spillover. As in Fudenberg and Tirole (1985), all information lags are assumed to be negligible. Of course, the instantaneous disclosure of the true quality of the innovation is quite stylized. However, it is the simplest way to capture the crucial role that informational spillovers play under uncertainty.[1]

Define the profit flow accruing to a firm when it alone adopts a 'good' innovation as Π_L, when its rival alone adopts as Π_F, and when both adopt as Π_2. Next, let Π_B be the profit flow if the innovation is 'bad'. In order to simplify matters assume $\Pi_B = \Pi_0$. Thus, an adopter can return to its old technology if the innovation fails. The following assumption regarding the relationships between the various flow profits will be maintained from the adoption models of Reinganum (1981) and Fudenberg and Tirole (1985):[2]

$$0 \leqslant \Pi_F \leqslant \Pi_0 < \Pi_2 < \Pi_L \text{ and } \Pi_L - \Pi_0 > \Pi_2 - \Pi_F$$

The first part of this assumption states that if a firm adopts a 'good' innovation, it benefits at the expense of its rival. The equality signs allow for the case of new markets with Π_L the monopoly profit and $\Pi_0 = \Pi_F = 0$. The second part implies that there is an advantage to adopting first. It can be shown that these assumptions are satisfied in a linear Cournot duopoly model.

The standard assumption on the undiscounted adoption costs, $k(t)$, in this context is that they are decreasing over time, but at a declining rate. Precisely, following Fudenberg and Tirole: $k'(t) < 0$, $k''(t) > 0$. Corner solutions are ruled out by assuming that adoption is initially not attractive, i.e. $(\mathrm{d}/\mathrm{d}t)(k(t)\, e^{-rt}|_{t=0} > \Pi_L - \Pi_F$, but will eventually occur, given any positive returns, i.e. $\lim_{t\to\infty} k(t) = 0$. The analysis can be considerably facilitated by introducing a monotonous transformation of time, namely $\tau(t) = 1 - e^{-rt}$, where r denotes the interest rate.[3] That is, the domain of time is normalized, without loss of generality, to the interval [0,1]. The discounted adoption costs can now be specified as a function of τ, $K(\tau)$, with the same properties as the undiscounted adoption costs $k(t)$: $K'(\tau) < 0$, $K''(\tau) > 0$, $K'(0) > \Pi_L - \Pi_F$, $\lim_{\tau\to 1} K(\tau) = 0$.

I first consider the decision problem of a firm that has already observed an adoption by the other firm. That firm is called the follower, the other the leader. It is worth emphasizing that this does not mean that the distribution of roles is given exogenously. In the next section, I will proceed to analyze the closed-loop equilibrium which involves an endogenous derivation of these roles. If the new technology turns out to be 'bad' (which happens with probability $1 - p$), the follower's optimal reaction is to never adopt in order to avoid wasting resources. If the new technology is 'good' (which happens with probability p), the follower

[1] For the same reason, any aspects of firm-specific uncertainty are omitted.

[2] The only difference lies in the equality signs.

[3] Riordan (1992) defines a discount factor $\Delta(t) = \mathrm{e}^{-rt}$ to represent an adoption date t. However, as t goes from zero to infinity, Δ takes values from one to zero.

chooses its optimal reaction to the leader's adoption date which is denoted by τ.[4] It turns out that the follower's optimal adoption date is $\tau_F^{opt} = \max\{\hat{\tau}_F, \tau\}$, where $\hat{\tau}_F$ is given by the equation

$$\frac{1}{r}(\Pi_2 - \Pi_F) = -K'(\hat{\tau}_F) \tag{1}$$

This is well-known from Fudenberg and Tirole (1985). The LHS of (1) is the marginal benefit from adopting as the follower. The RHS gives the marginal adoption cost. Taking the optimal follower reaction into account, the expected payoffs for the leader and the follower can be specified as a function of the leader's adoption date alone. Let $L(\tau)$ and $F(\tau)$ be the expected payoffs (in present value terms) to the leader and follower. If a firm is the first adopter, it receives an expected payoff of

$$L(\tau) = \frac{1}{r}\left[\underbrace{\Pi_0 + p(1-\tau)(\Pi_2 - \Pi_0)}_{\text{joint-adoption profits}} \underbrace{+p\left(\tau_F^{opt} - \tau\right)(\Pi_L - \Pi_2)}_{\text{strategic advantage}}\right] - K(\tau)$$

If a firm is the follower, it has an expected payoff of

$$F(\tau) = \frac{1}{r}\left[\underbrace{\Pi_0 + p(1-\tau)(\Pi_2 - \Pi_0)}_{\text{joint-adoption profits}} \underbrace{-p\left(\tau_F^{opt} - \tau\right)(\Pi_2 - \Pi_F)}_{\text{strategic disadvantage}}\right] - pK\left(\tau_F^{opt}\right)$$

The first component of $L(\tau)$ and $F(\tau)$ gives the present value of the expected benefits from adoption. These consist of the profits received when both firms make use of the new technology at the same time (joint-adoption profits) plus the additional profits for the leader (strategic advantage) or minus the loss in profits for the follower (strategic disadvantage) during the period in which the leader is the only adopter.[5] The last component gives the expected discounted adoption costs, with an advantage for the follower due to the informational spillover.

In the extreme case of $p=1$, i.e. when there is certainty of success, the payoff functions reduce to those used in the Fudenberg and Tirole model. Fudenberg and Tirole distinguish between two possible configurations that are displayed in Fig. 1a and b. $L(\tau)$ is concave in τ for all $\tau \leq \hat{\tau}_F$ (the 'diffusion range') by the properties of

[4] The reaction lag of the follower is assumed to be negligible. The follower may therefore follow suit immediately, i.e. consecutively, but at the 'same' τ. See footnotes 6 and 7.

[5] Remember that $\tau = 1 - e^{-rt}$.

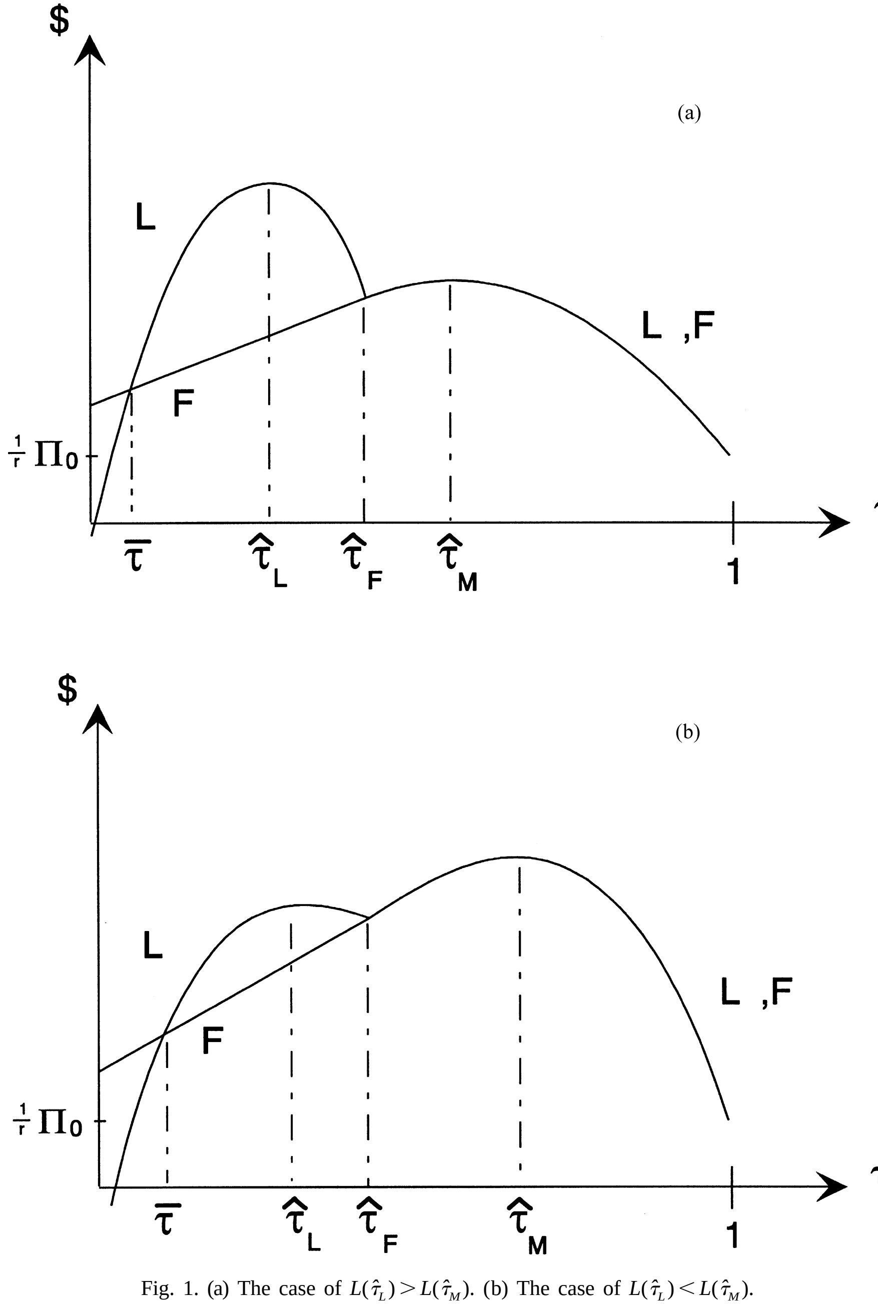

Fig. 1. (a) The case of $L(\hat{\tau}_L) > L(\hat{\tau}_M)$. (b) The case of $L(\hat{\tau}_L) < L(\hat{\tau}_M)$.

$K(\tau)$, and achieves a local maximum at $\hat{\tau}_L$. $F(\tau)$ is linear and increasing over this range. Both functions, $L(\tau)$ and $F(\tau)$, are concave in τ for $\tau \geqslant \hat{\tau}_F$ (the 'joint-adoption range'). The local maximum of $L(\tau)$ in this range is denoted by $\hat{\tau}_M$. In Fig. 1a, the global maximum of $L(\tau)$ is $\hat{\tau}_L$, and in Fig. 1b, it is $\hat{\tau}_M$. The kink in the $L(\tau)$-curve at $\hat{\tau}_F$ is due to the optimal reaction of the follower, i.e. to adopt at $\tau_F{}^{opt} = \max\{\hat{\tau}_F, \tau\}$ if the innovation is 'good'.

The general properties described for the case of $p=1$ remain unchanged under uncertainty. Moreover, $\hat{\tau}_F$ is clearly independent of p since the follower decides whether or not to adopt being informed about the true value of the innovation. $\hat{\tau}_L$ solves the first-order condition for $\max_{\tau \in [0,\hat{\tau}_F]} L(\tau)$, i.e.

$$\frac{1}{r} p(\Pi_L - \Pi_0) + K'(\hat{\tau}_L) = 0, \tag{2}$$

$\hat{\tau}_M$ solves the first-order condition for $\max_{\tau \in [\hat{\tau}_F,1]} L(\tau)$, i.e.

$$\frac{1}{r} p(\Pi_2 - \Pi_0) + K'(\hat{\tau}_M) = 0. \tag{3}$$

But technological uncertainty affects the relative positions of $L(\tau)$ and $F(\tau)$. Two underlying dichotomies turn out to be crucial. First, if $p<1$, $F(\tau)$ may lie above or below $L(\tau)$ at the local maximum of $L(\tau)$ in the 'diffusion range'. To see this, note that if $p=0$, i.e. in the case of complete certainty of failure, $F(\tau)=(1/r)\Pi_0 > (1/r)\Pi_0 - K(\tau) = L(\tau)$ for all $\tau > 1$, while $F(\hat{\tau}_L) < L(\hat{\tau}_L)$ if $p=1$. Hence, at least one critical value, denoted by p^*, must exist such that Definition 1 holds.

Definition 1. Let p^* denote the value of $p \in]0,1[$ that satisfies the condition

$$L(\hat{\tau}_L(p)) = F(\hat{\tau}_L(p)), \tag{4}$$

where $\hat{\tau}_L(p) = \arg\max_{\tau \in [0,\hat{\tau}_F]} L(\tau)$.

For the second dichotomy, first note that if $p=0$, $L(\tau)$ is a strictly increasing function. Hence, for small enough p, $L(\tau)$ definitely achieves its global maximum in the 'joint-adoption range'. But if for $p=1$ the global maximum lies in the 'diffusion range', at least one critical value, denoted by p^{**}, must exist that satisfies Definition 2.

Definition 2. Let p^{**} denote the value of $p \in]0,1[$ that satisfies the condition

$$L(\hat{\tau}_L(p)) = L(\hat{\tau}_M(p)), \tag{5}$$

where $\hat{\tau}_L(p) = \arg\max_{\tau \in [0,\hat{\tau}_F]} L(\tau)$ and $\hat{\tau}_M(p) = \arg\max_{\tau \in [\hat{\tau}_F,1]} L(\tau)$. If $L(\hat{\tau}_L(p)) < L(\hat{\tau}_M(p))\ \forall p$, then $p^{**} \equiv 1$.

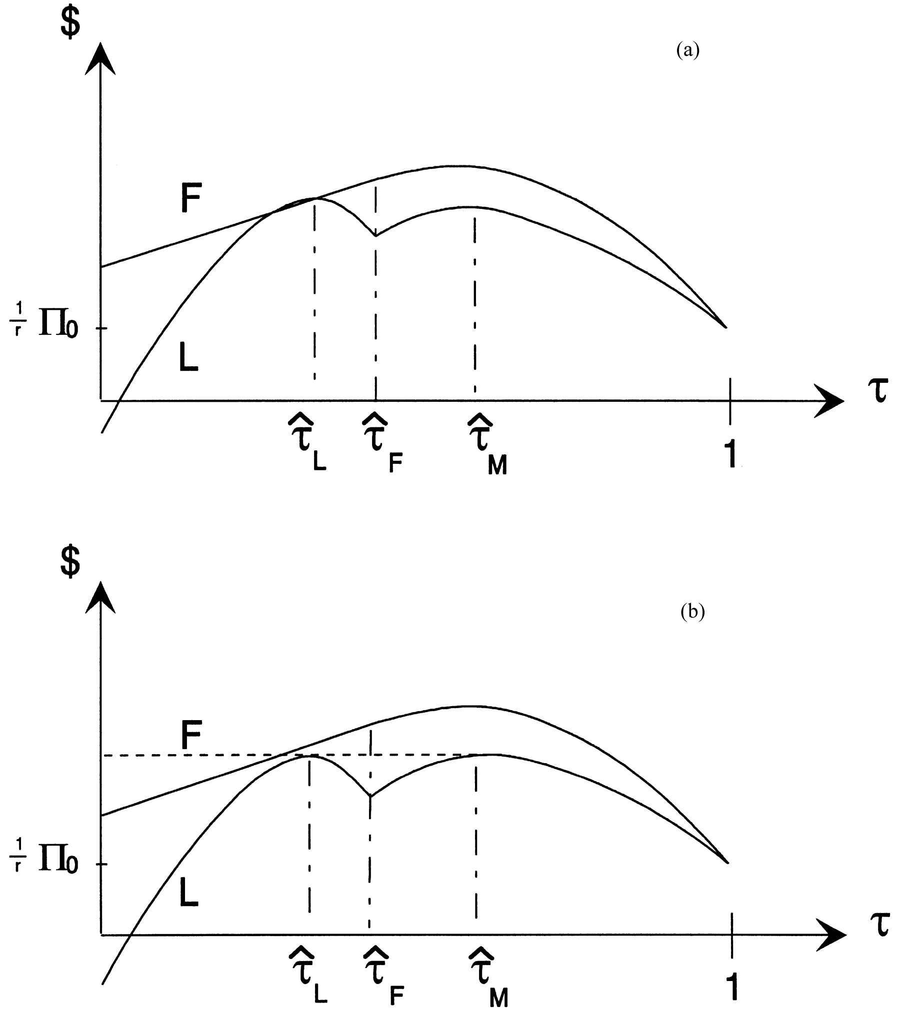

Fig. 2. (a) The case of $p=p^*$. (b) The case of $p=p^{**}$.

As is illustrated in Fig. 2a, $L(\hat{\tau}_L)=F(\hat{\tau}_L)$ if $p=p^*$. Fig. 2b depicts the case of $p=p^{**}$, i.e. when $L(\hat{\tau}_M)=L(\hat{\tau}_L)$.

3. Closed-loop equilibria

At any point in time, represented by $\tau\in[0,1]$, each firm chooses whether to adopt (if it has not yet adopted) depending on the previous history. Time is continuous.[6] Information and reaction lags are assumed to be negligible. So if one firm adopts, the other may follow consecutively, but at the same instant of time.[7] A firm's pure strategy is simply a map from any adoption date τ to the action set {Adoption, No Adoption} conditioned on whether its rival has adopted previously. I will focus on closed-loop equilibria of the game. Thus, each firm's strategy must be a best response to the other firm's strategy, starting from every $\tau \in [0,1]$.

The decision if and when to adopt a new technology whose returns are uncertain can take two fundamentally different forms of competition: a preemption game and a waiting game. The incentive for preemptive adoption results from the strategic advantage of being (temporarily) the only user of the new technology. For $L(\hat{\tau}_L) - F(\hat{\tau}_L) > 0$, the timing structure in the 'diffusion range' is therefore called a preemption game. Respectively, it is a waiting game if $L(\hat{\tau}_L) - F(\hat{\tau}_L) < 0$. In the 'joint-adoption range' the timing is always structured as a waiting game if $p < 1$. The following two lemmas show how the general structure of the game crucially depends on the probability that the innovation is profitable.

Lemma 1. $\exists$ *unique p^* (as defined above), such that the timing competition for $\tau \leqslant \hat{\tau}_F$ is a preemption game if $p > p^*$, and a waiting game if $p < p^*$.*

Lemma 2. $\exists$ *unique p^{**} (as defined above), such that $L(\hat{\tau}_L) > L(\hat{\tau}_M)$ if $p > p^{**}$, and $L(\hat{\tau}_L) < L(\hat{\tau}_M)$ if $p < p^{**}$.*

Example 1. Consider a linear inverse demand function $P = 1 - Q$, constant marginal cost $c = \frac{3}{4}$, a process innovation that reduces the marginal cost to $c - \varepsilon = \frac{5}{8}$ and Cournot competition. The undiscounted adoption costs take the form of $k(t) = e^{-\alpha t}$, where α is the constant rate of technological progress. Thus, $K(\tau) = (1 - \tau)^{\frac{r+\alpha}{r}}$. Fix $\alpha = \frac{1}{5}$ and $r = \frac{1}{25}$. Solving numerically yields $p^* \simeq 0.85$ and $p^{**} \simeq 0.95$.

Example 2. Consider a new market with $P = 1 - Q$, $c = 1$, $c - \varepsilon = \frac{5}{8}$ and Cournot

[6] Fudenberg and Tirole (1985) note that 'continuous time' is a convenient mathematical construction intended to represent the notion of very short time lags. However, there are certain technical problems of modelling closed-loop strategies in continuous time (see Simon and Stinchcombe, 1989). In particular, in order to solve for pure strategy equilibria, we need a way to represent the limit of discrete-time outcomes in which agents move at consecutive grid points. This issue is resolved by representing limit histories as vector pairs (see next footnote). The continuous-time representation of the limit of discrete-time equilibria in mixed strategies necessitates the use of several more technicalities (see Fudenberg and Tirole, 1985). However, in order to show that second-mover advantages are possible, we can concentrate on pure strategies.

[7] Formally, a history h is a string of 'jumps' that the firms have made during the play of the game. A 'jump' is denoted by a pair (τ, a), where $a \in$ {Adoption, No Adoption}. To allow firms to jump consecutively, but at the 'same' instant of time, the vector of jump-times τ of h need not be strictly increasing (see Simon and Stinchcombe, 1989).

competition when both firms have entered. $K(\tau)=(1-\tau)^{\frac{r+\alpha}{r}}$, with $\alpha=\frac{1}{5}$ and $r=\frac{1}{25}$. Solving numerically yields $p^*\simeq 0.75$ and $p^{**}\simeq 0.6$.

The examples show that there is no general relationship between the values of p^* and p^{**}. Define therefore $\bar{p}=\max\{p^*,\ p^{**}\}$.

If $p>\bar{p}$, the unique closed-loop equilibrium outcome is that firm i $(=1,2)$ adopts at the earliest preemption date $\bar{\tau}$ and firm j $(\neq i)$ follows suit at $\hat{\tau}_F$ if the innovation is 'good', where $\bar{\tau}$ is the smallest $\tau\in[0,1]$ such that $L(\bar{\tau})=F(\bar{\tau})$. Fudenberg and Tirole (1985) have proved for the case of complete certainty of success, i.e. $p=1$, that this solution is implemented by a unique equilibrium in mixed strategies. In this equilibrium, each firm has an equal chance of adopting preemptively at $\bar{\tau}$ just before a potential first-mover advantage arises. The other firm's optimal reaction is then to delay adoption until $\hat{\tau}_F$. While the formal proof necessitates the use of quite technical arguments, the intuition behind it is straightforward. Neither firm can obtain more than $L(\hat{\tau}_L)$. Hence, each firm would like to be first at $\hat{\tau}_L$. But if a firm, say firm i, plans to wait until $\hat{\tau}_L$, then firm j would like to adopt just slightly earlier to reap most of the potential first-mover advantage. However, then firm i would do better to preempt firm j slightly, and so forth. Fudenberg and Tirole's argument is perfectly applicable in the case of uncertainty in which $L(\hat{\tau}_L)>F(\hat{\tau}_L)$. Hence, for $p>\bar{p}$ the unique closed-loop equilibrium involves preemption and rent-equalization.

Now consider the case of $p<\bar{p}$. The following proposition establishes the existence of a pure strategy equilibrium and characterizes it. Proposition 2 Pareto-ranks the equilibria.

Proposition 1. *If $p<\bar{p}$, there is a unique pure strategy equilibrium (modulo relabelling of firms). It involves a strict follower-advantage. In this equilibrium firm $i(=1,2)$ adopts at the global maximum of $L(\tau)$, $\hat{\tau}_L$ or $\hat{\tau}_M$, and firm j $(\neq i)$ follows suit at $\hat{\tau}_F$ or $\hat{\tau}_M$, respectively, if the innovation is 'good'.*

The pure strategy equilibrium is asymmetric. In principle, the competitors' expectations about the rival's strategies determine the equilibrium outcome. If, for example, firm 1 believes that 2 never adopts first, 1 may choose to adopt first. Likewise, if 2 has the reputation of being likely to adopt first, it may be optimal for firm 1 to wait until 2 has adopted. Nalebuff and Riley (1985) show that even with only payoff-irrelevant observational differences between competitors, very asymmetric behaviour is evolutionally viable in a waiting game. For $0<p<\bar{p}$, there are additional equilibria in mixed strategies. As argued by Fudenberg and Tirole (1985), the most reasonable outcome to be expected is the equilibrium that Pareto-dominates all others. Pareto-ranking yields that firms will prefer the pure strategy equilibrium, which involves a follower-advantage.

Proposition 2. *If $p<\bar{p}$, the pure strategy equilibrium, which involves a follower-advantage, Pareto-dominates any other equilibria.*

Finally, consider the case of $p=\bar{p}$. Suppose first that $p=\bar{p}=p^{**}$. If $p=1$,

$L(\hat{\tau}_M) > L(\hat{\tau}_L)$ as illustrated in Fig. 1b.[8] For this case, Fudenberg and Tirole have shown that there are two types of equilibria. One type is the preemptive one described above. Another is a class of pure-strategy equilibria involving joint-adoption. The latter is due to the fact that there is a $\tau \in [\hat{\tau}_F, \hat{\tau}_M]$ such that no firm cannot gain by preempting before this date, given the rival firm waits until that date. Instead, each firm can credibly threaten to adopt immediately if the other does. Fudenberg and Tirole show that joint-adoption at $\hat{\tau}_M$ is the Pareto-optimal choice.[9] Under uncertainty, the timing competition for $\tau \leqslant \hat{\tau}_F$ is still a preemption game, i.e. $L(\hat{\tau}_L) > F(\hat{\tau}_L)$, but both local maxima of $L(\tau)$ are global ones, i.e. $L(\hat{\tau}_L) = L(\hat{\tau}_M)$, since $p = p^{**} > p^*$. Thus, similarly, there is one preemption equilibrium, and another one in which one firm adopts at $\hat{\tau}_M$ and the other follows suit immediately if the innovation is 'good'. The equilibrium strategies that support this joint-adoption outcome are the same as for $p < \bar{p} = p^{**}$. This equilibrium can be shown to be Pareto-dominant, with equilibrium payoffs of $L(\hat{\tau}_M) < F(\hat{\tau}_M)$. Suppose now that $p = \bar{p} = p^*$ (as depicted in Fig. 2a). It is clear that no firm can gain from preemptive adoption since $L(\hat{\tau}_L) = F(\hat{\tau}_L)$. Hence, the equilibrium entails adoption at $\hat{\tau}_L$ and $\hat{\tau}_F$ and payoffs $L(\hat{\tau}_L) = F(\hat{\tau}_L)$.

The resulting equilibrium payoffs as a function of the probability of failure are illustrated in Fig. 3a for the case of $\bar{p} = p^{**}$. It reveals a surprising discontinuity. Increasing the probability of failure from slightly below the critical value leads to an upwards jump of the equilibrium payoffs for both firms.[10] To see the economics of this issue consider the case of $p^* < p \leqslant p^{**}$. From above we know that $\hat{\tau}_M$ is the global maximum of $L(\tau)$. In equilibrium firms obtain $L(\hat{\tau}_M)$ and $F(\hat{\tau}_M)$, with $L(\hat{\tau}_M) < F(\hat{\tau}_M)$. If the probability of failure is decreased from $1 - p^{**}$ a tiny bit below this critical value, the competition over adoption times will take the form of a contest for being first at $\hat{\tau}_L$, the new global maximum of $L(\tau)$. Due to the threat of preemption, rents are dissipated and both firms' equilibrium payoffs jump down to $L(\bar{\tau}) = F(\bar{\tau})$.

A similar discontinuity of the equilibrium payoffs can be found for $\bar{p} = p^*$ (see Fig. 3b). Consider the payoffs in the case of $p^{**} < p = p^*$ (as depicted in Fig. 2a). On the one hand, an increase in the probability of failure just above the critical value leads to a waiting game, with a continuous increase in the leader's adoption date $\hat{\tau}_L$. Hence, the equilibrium payoffs, $L(\hat{\tau}_L)$ and $F(\hat{\tau}_L)$, are continuously reduced.

[8] Remember that $p^{**} = 1$ when $L(\hat{\tau}_M) > L(\hat{\tau}_L)\ \forall p$, according to Definition 2.

[9] The argument for coordination on joint-adoption at $\hat{\tau}_M$ in this case is strengthened by the analysis above. Introducing a small probability of failure yields joint-adoption at $\hat{\tau}_M$ as the only pure-strategy closed-loop equilibrium outcome.

[10] This result is similar to the one by Benoit (1985) in the context of R&D. He finds a non-monotonicity of the innovator's profits in the probability of success. The key difference is that the roles of the firms, as well as the arrival of information regarding the profitability of the innovation are exogenous in his R&D model. Preemptive behaviour and free-riding are thus ruled out.

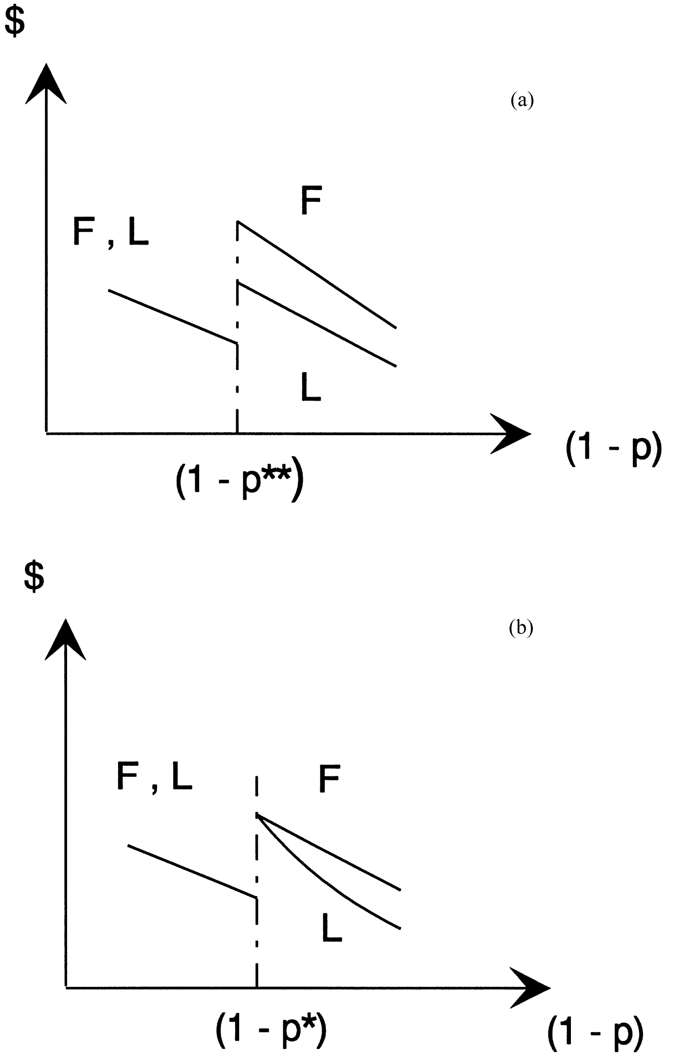

Fig. 3. (a) The equilibrium payoffs as a function of $(1-p)$ when $\bar{p}=p^{**}$. (b) The equilibrium payoffs as a function of $(1-p)$ when $\bar{p}=p^{*}$.

On the other hand, a small decrease in $1-p$ just below the critical value causes a change to a preemption game. The leader's adoption date therefore switches from $\hat{\tau}_L$ to the earliest preemption date $\bar{\tau}$, and both firms' equilibrium payoffs change from $L(\hat{\tau}_L)$ to $L(\bar{\tau})$. Whether this means a downward jump or not, however, depends on the impact of the leader's adoption on the follower's profit flow, i.e.

$\Pi_0 - \Pi_F$. To see this, consider the extreme case in which $\Pi_0 - \Pi_F$ is zero. The payoff configuration is then similar to that in Fig. 2a. The only difference is that the slope of $F(\tau)$ in the 'diffusion range' is zero, since the leader's timing in this range leaves the follower's payoff unaffected. In this case, $L(\tau)$ and $F(\tau)$ are tangent to each other at $\hat{\tau}_L$ for $\bar{p} = p^*$. Thus $\hat{\tau}_L = \bar{\tau}$, and $L(\bar{\tau}) = F(\tau)\ \forall \tau \in [0, \hat{\tau}_F]$. A decrease in $1-p$ below the critical value therefore leads to a continuous change in the equilibrium payoffs. But since $F(\tau)$ is increasing in p, a decrease in $1-p$ must be beneficial for both firms. However, as $\Pi_0 - \Pi_F$, i.e. the slope of $F(\tau)$ in the 'diffusion range', is increased, the change in equilibrium payoffs from $L(\hat{\tau}_L)$ to $L(\bar{\tau})$ becomes a downward jump. By the previous lemmas and propositions, these considerations regarding the discontinuity of equilibrium adoption dates and payoffs in the probability that the innovation is profitable are summarized in the following proposition.

Proposition 3. *When p is increased from just below to just above $p = p^{**}$, the equilibrium adoption dates of both firms jump downward from $\hat{\tau}_M$ to $\bar{\tau}$ and $\hat{\tau}_F$, and the equilibrium payoffs are discontinuously reduced. When p is increased from just below to just above $\bar{p} = p^*$, the equilibrium adoption date of the leader switches from $\hat{\tau}_L$ to $\bar{\tau}$, that of the follower remains unchanged, and the equilibrium payoffs may or may not jump down.*

Finally, it is easy to show that the first adoption occurs later the higher the probability of failure, with a decrease in the extent of dispersion between the firms' adoption timings in all sequential adoption equilibria.[11] Recently, Mansfield (1993) has studied the speed of adoption of flexible manufacturing systems. Among other things, he observed that the first major firm to begin adopting tended to adopt later in the United States than in Japan. In addition, he found that the early users of this technology in the United States had expected a rate of return that was, on average, 6 percentage points above the minimum rate of return required for investments of this sort, while the users in Japan had expected it to be about 25 percentage points above the minimum rate of return. Thus, the quite intuitive finding that the leader's adoption occurs later the lower the probability that the new technology is profitable seems to be consistent with the empirical observations.

[11] For $p \leq \bar{p}$, the leader's equilibrium adoption date is decreasing in p by conditions (2) and (3) and the properties of $K(\tau)$. For $p > \bar{p}$, one can show by the implicit function theorem that the earliest preemption date $\bar{\tau}$ is decreasing in p. $\hat{\tau}_F$ is independent of p because of the informational spillover (see condition (1)). Stenbacka and Tombak (1994) analyze the impact of changes in a firm's hazard rate of successfully implementing the new technology on the extent of dispersion between adoption dates. Contrary to the present paper, this type of uncertainty is firm-specific. The date of the second adoption may therefore change as well.

4. Welfare

Welfare is defined as the present value of the intertemporal stream of social benefits (firm profits and consumer surplus) minus discounted adoption cost. Let C_0 be the (Marshallian) consumer surplus flow, when both firms make use of the old technology. C_k ($k=1,2$) is the consumer surplus flow if k firms have adopted a 'good' innovation. Assume that $C_2 > C_1 > C_0$ which could be due to an increase in output in the number of adopters. This assumption can be shown to hold in a linear Cournot duopoly model, and is the case analyzed by Jensen (1992a). Welfare is given by

$$\begin{aligned} W(\tau_L, \tau_F) = & \underbrace{\frac{1}{r}\left[(2\Pi_0 + C_0) + p(1-\tau_L)(2\Pi_2 + C_2 - 2\Pi_0 - C_0)\right]}_{\text{joint-adoption benefits}} \\ & \underbrace{-\frac{1}{r}p\left(\max\{\tau_F, \tau_L\} - \tau_L\right)(2\Pi_2 + C_2 - \Pi_L - \Pi_F - C_1)}_{\text{diffusion effect}} \\ & -K(\tau_L) - pK(\tau_F), \end{aligned}$$

where $\tau_L \leq \tau_F$ denote the adoption dates of the leader and follower, respectively. The expected social benefits consist of the profit and consumer surplus flows received when both firms make use of the new technology at the same time (joint-adoption benefits) and the change in profit and consumer surplus flows during the period in which the leader is the only adopter (diffusion effect). The last two components of W give the discounted adoption cost of the leader and follower.

As in the equilibrium analysis, there are two cases to consider. First, both firms adopt consecutively, but at the same date. Second, both firms adopt at different dates. Which case coincides with the welfare optimum depends on the parameter values and underlying dynamics as expressed by the cost function $K(\tau)$. Thus, the Riordan (1992) approach of comparing the privately optimal adoption dates with the socially optimal ones becomes a considerably complicated problem. In fact, it is not possible to completely characterize all circumstances under which privately optimal behaviour does or does not fail to maximize expected welfare analytically. However, by relating the joint-adoption [diffusion] equilibrium dates to the adoption dates in the respective joint-adoption [diffusion] welfare maximum, one can still prove the following normative conclusions about sufficiently small changes of the equilibrium adoption dates.[12]

[12] It is clear that adoption by the follower will only be privately and socially optimal if the innovation turns out to be 'good'. The reference to this condition will be neglected in the following.

Proposition 4. *If $p \leqslant p^{**}$, then both firms adopting earlier increases W.*

The normative assessment regarding the diffusion equilibrium involves some ambiguities which can be eliminated by focusing on a Cournot duopoly in the product market with linear demand and constant marginal costs (the example considered by Jensen, 1992a). The following restriction on the relative magnitude of the consumer surplus flows can be shown to hold in such a Cournot duopoly model, in the non-drastic case, as well as in the drastic one.[13]

$$C_1 - C_0 > \Pi_0 - \Pi_F \text{ and } C_2 - C_1 < \Pi_L - \Pi_2 \tag{6}$$

Condition (6) implies that the increase in consumer surplus flow is greater than the reduction in the rival firm's profit flow for the first adoption, but smaller for the second, provided that the innovation succeeds. This could be due to the fact that output increases in the number of adopters if the innovation is 'good'.

Proposition 5. (i) *If $p \leqslant p^*$ and $p > p^{**}$, or $p > p^*$ and $p > p^{**}$ and $K'(\hat{\tau}_L) - K'(\bar{\tau}) < \frac{1}{r} p[(C_1 - C_0) - (\Pi_0 - \Pi_F)]$, then the leader adopting earlier and the follower adopting later increases W.* (ii) *If $p > p^*$ and $p > p^{**}$ and $K'(\hat{\tau}_L) - K'(\bar{\tau}) > \frac{1}{r} p[(C_1 - C_0) - (\Pi_0 - \Pi_F)]$, then both firms adopting later increases W.*

The normative assessment of the equilibrium timing is determined by the relative magnitude of four effects.

1. The preemption effect: preemption accelerates adoption inefficiently from the firms' point of view.
2. The business-stealing effect: earlier adoption increases the expected loss in profits of the rival firm.
3. The informational-spillover effect: the informational spillover delays the leader's adoption inefficiently from the firms' point of view.
4. The consumer-surplus effect: later adoption decreases expected consumer surplus that is maximized if both firms adopt immediately.

The first two effects conflict with the last two. However, not all of them matter for each of the different equilibrium outcomes. In particular, in a waiting game involving joint-adoption at $\hat{\tau}_M$ (i.e. if $p \leqslant p^{**}$), the only effects that are non-zero are the informational-spillover effect, i.e. $\frac{dF(\tau)}{d\tau}\big|_{\tau=\hat{\tau}_M} < 0$, and the consumer-surplus effect, i.e. $-\frac{1}{r} p(C_2 - C_0)$. Thus, social welfare is improved when both firms adopt earlier. However, in a waiting game involving diffusion (i.e. if $p < p^*$ and $p > p^{**}$), it turns out that welfare is increased by an earlier initial adoption since the consumer surplus effect, $-\frac{1}{r} p(C_1 - C_0)$, dominates the impact on the

[13] When the innovation is drastic, the first adopter becomes a monopolist until the other firm adopts. See Arrow (1962).

follower's profits, $\frac{dF(\tau)}{d\tau}\big|_{\tau=\hat{\tau}_L} = \frac{1}{r}p(\Pi_0 - \Pi_F)$, and by a later follow-on adoption because the respective business-stealing effect, $\frac{dL(\tau)}{d\hat{\tau}_F} = \frac{1}{r}p(\Pi_L - \Pi_2)$, outweighs the consumer surplus effect, $-\frac{1}{r}p(C_2 - C_1)$. Finally, in a preemption game (i.e. if $p > p^*$ and $p > p^{**}$), the follower's adoption is too early for the same reason as in the waiting game involving diffusion, while three effects turn out to be crucial for the normative assessment of the leader's equilibrium adoption date. Depending on whether the preemption effect, $K'(\hat{\tau}_L) - K'(\bar{\tau})$ (see Appendix A), is greater than, equal to, or smaller than the difference between the conflicting consumer-surplus and business-stealing effects, the leader adopts too early, optimally, or too late. Thus, the net impact depends on the marginal decrease in the cost of adoption, or in other words on the rate of technological progress. If this rate is high (initially), then the leader is likely to be too early. The preemption incentive would then induce one firm to expend too much resources on adoption today at the expense of adopting at lower cost in the future.

The welfare results suggest that policy intervention in the diffusion process may be justified, and confirm the Stoneman and Diederen (1994) conjecture that 'diffusion policy should not proceed upon a presumption that faster is always better' (p. 929). However, slower is also not always better. There are well-defined contexts in which a generally higher adoption speed is socially beneficial (Proposition 4), and others in which the opposite is true (Proposition 5(ii)). It is shown that in all other circumstances social welfare is improved by an earlier first and later second adoption (Proposition 5(i)). Thus, if policy makers want to intervene in the diffusion process, then they should enhance the incentive to adopt in the first case and reduce it in the second. However, in the third case it seems appropriate to protect the first adopter by delaying future adoptions. A longer exclusive use of the innovation should result in faster adoption by the first mover. In conclusion, it is necessary that any diffusion policy adequately depends on the probability that the innovation is profitable and the rate of technological progress.

Jensen (1992a) considers a static duopoly model, and finds that social welfare is maximized when no firm adopts if the probability that the innovation is 'good' is below a certain level. In the present model, however, it can easily be derived from conditions (11), (12), and (13) (see Appendix A) that adoption is socially optimal for all $p > 0$, but with later adoption dates for smaller values of p.

5. Conclusion

This paper extends the analysis of adoption and diffusion by Fudenberg and Tirole (1985) to include uncertainty regarding the profitability of a new technology. It is demonstrated that the timing competition switches in a fundamental way from a preemption game to a waiting game as the probability that the innovation is profitable decreases. Depending on this parameter, the closed-loop equilibria therefore exhibit payoff-equalization due to the threat of preemption or second-mover advantages because of informational spillovers. The model thus predicts the follower to be better-off, on average, which corresponds to recent empirical findings by Tellis and Golder (1996). Furthermore, the analysis in the present paper shows that the change in the timing structure from a preemption game to a waiting game leads to a surprising result. Both firms may benefit from a higher degree of failure.

The welfare analysis reveals that the normative assessment of policies to speed or slow the adoption process depends on the relative magnitude of four main effects that can also be found in the R&D literature: the preemption effect, the business-stealing effect, the informational-spillover effect and the consumer-surplus effect. It is shown that any policy intervention should adequately depend on the probability that the new technology is profitable and the rate of technological progress.

Related to this paper is the literature on strategic investment in a new market under uncertainty that focuses on the trade-off between commitment and flexibility.[14] Recently, Maggi (1996) has analyzed a two-period model in which firms can choose capital levels in both periods and compete in the product market thereafter. In his model, a potential first-mover advantage is of the Stackelberg-leader type, i.e. the pioneer firm commits to a capital level that is higher than the Cournot level if capital stocks are strategic substitutes. A potential second-mover advantage is due to the fact that uncertainty is resolved in the second period. He finds that the equilibria of the game are asymmetric, provided that the likelihood that the market is profitable is high enough. One firm is shown to choose a preemptive strategy and the other a flexible wait-and-see strategy in spite of the fact that firms are ex-ante identical. These equilibria entail a first-mover advantage. By contrast, in the infinite-horizon model of the present paper in which investing earlier is more costly, no firm can credibly commit to follow a wait-and-see strategy if the probability of success is high. The respective equilibrium therefore involves rent equalization and dissipation.[15] The model admits asymmetric equilibria in which one firm follows a preemptive strategy and the other a wait-and-see strategy for low probabilities of success. In these equilibria, both firms prefer to be the second mover.

One potential extension of the model would explore the timing of adoption when there are lags between the adoption decision and the disclosure of the quality of the new technology. When information about the profitability of the innovation arrives with a sufficiently long lag, the follower may choose to adopt before the arrival of information. Thus, as the length of this lag is increased, any potential

[14] I am grateful to a referee for pointing this out to me.

[15] See Anderson and Engers (1994) for an analysis of preemptive entry-timing in a Stackelberg model with $n \geqslant 2$ firms.

second-mover advantage is eliminated. This information lag could also be made endogenous by information-gathering activities of the follower. The follower's adoption date would then be an optimal stopping problem. Apparently, the results of this paper still hold as long as the lag is sufficiently small. Finally, technological progress could be modelled as an increase in the probability of success over time instead of a decrease in the cost of adoption. The optimal reaction of the follower would then always be to follow suit immediately if the innovation is 'good'. This would eliminate any potential first-mover advantage.

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Appendix A

Proof of Lemma 1. Define $D(p) = L(\hat{\tau}_L(p)) - F(\hat{\tau}_L(p))$. The proof that there is a unique p^* consists of two parts. First, it will be shown that $D<0$ if p is small, and $D>0$ if p is high. Second, D has to be increasing in p.

(i) From condition (2) we know that $\hat{\tau}_L(p)$ is decreasing in p. By (1) and (2), $\hat{\tau}_L(p) = \hat{\tau}_F$ if $p = \frac{\Pi_2 - \Pi_F}{\Pi_L - \Pi_0} < 1$. But $L(\hat{\tau}_F) < F(\hat{\tau}_F)$ for all $p<1$. Thus, $D<0$ for $p = \frac{\Pi_2 - \Pi_F}{\Pi_L - \Pi_0}$. Next, if $p=1$, $L(\hat{\tau}_L) > L(\hat{\tau}_F)$ and $L(\hat{\tau}_F) = F(\hat{\tau}_F)$. Since $\frac{\mathrm{d}F(\tau)}{\mathrm{d}\tau} \geqslant 0$ for $\tau \leqslant \hat{\tau}_F$, $F(\hat{\tau}_F) \geqslant F(\tau)$ for $\tau < \hat{\tau}_F$. By (1), (2), and the properties of $K(\tau)$, $\hat{\tau}_L < \hat{\tau}_F$. It follows that $D>0$ for $p=1$.

(ii) $D = \frac{1}{r} p(\hat{\tau}_F - \hat{\tau}_L(p))(\Pi_L - \Pi_F) - K(\hat{\tau}_L(p)) + pK(\hat{\tau}_F)$ for $\hat{\tau}_L \leqslant \hat{\tau}_F$. Taking the derivative with respect to p and making use of condition (2) gives $D'(p) = \frac{1}{r}(\hat{\tau}_F - \hat{\tau}_L(p))(\Pi_L - \Pi_F) + K(\hat{\tau}_F) - \hat{\tau}_L'(p)\frac{1}{r}p(\Pi_0 - \Pi_F)$ which is strictly positive. The result follows immediately. ■

Proof of Lemma 2. It needs to be shown that there is a unique p^{**} if $L(\hat{\tau}_L) < L(\hat{\tau}_M)$ does not hold for all p. Define

$$L_L(\tau) = \frac{1}{r}\,[\Pi_0 + p(1-\tau)(\Pi_2 - \Pi_0) + p(\hat{\tau}_F - \tau)(\Pi_L - \Pi_2)] - K(\tau)$$

$$\text{and } L_M(t) = \frac{1}{r}\,[\Pi_0 + p(1-\tau)(\Pi_2 - \Pi_0)] - K(\tau)$$

as two independent functions of $\tau \in [0,1]$. Now, $\hat{\tau}_L(p)$ satisfies the first-order condition of $\max_{\tau\in[0,1]} L_L(\tau)$, and $\hat{\tau}_M(p)$ satisfies the first-order condition of $\max_{\tau\in[0,1]} L_M(\tau)$. These conditions are equal to (2) and (3). Next, define $G(p) = L_M(\hat{\tau}_M(p)) - L_L(\hat{\tau}_L(p))$. Consider the case of $G(1) < 0$ (as depicted in Fig. 1a). We need to show that $G(p) = 0$ only once for $p > 0$. In what follows it will be shown that $G(p)$ is strictly concave in p, where $G(0) = 0$ and $G(1) < 1$. Second, it will be demonstrated that $G(p) > 0$ if p is low.

(i) $G(p)$ can be written as $G(p) = -\frac{1}{r} p(1-\hat{\tau}_L)(\Pi_L - \Pi_0) + \frac{1}{r} p(1-\hat{\tau}_M)(\Pi_2 - \Pi_0) + \frac{1}{r} p(1-\hat{\tau}_F)(\Pi_L - \Pi_2) - K(\hat{\tau}_M) + K(\hat{\tau}_L)$. Since $\hat{\tau}_M = \hat{\tau}_L = 1$ if $p = 0$, and $K'(1) = 0$, it follows that $G(0) = 0$. Next, G is strictly concave in p if the slope of the tangent line at p_0 is greater than that of the chord joining $G(p_1)$ and $G(p_0)$, if $p_1 > p_0$ for any $p = p_1$, i.e.

$$G(p) < G(p_0) + G'(p_0)(p - p_0) \text{ for any } p > p_0. \tag{7}$$

Let $p_0 = 0$, so condition (7) reduces to

$$G(p) < pG'(0) \text{ for any } p > 0 \tag{8}$$

since $G(0) = 0$. Taking the derivative of G with respect to p at $p = 0$ yields $G'(0) = \frac{1}{r}(1-\hat{\tau}_F)(\Pi_L - \Pi_2)$. Substituting $G(p)$ and $G'(p)$ into (8), taking (2) and (3) into account, and rearranging terms yields

$$K(\hat{\tau}_L) - K(\hat{\tau}_M) < \hat{\tau}_L K'(\hat{\tau}_L) - \hat{\tau}_M K'(\hat{\tau}_M) - K'(\hat{\tau}_L) + K'(\hat{\tau}_M) \tag{9}$$

$K(\tau)$ is assumed to be strictly convex in τ. From conditions (2) and (3) it can be straightforwardly shown that $\hat{\tau}_L < \hat{\tau}_M \ \forall p > 0$. Thus, strict convexity of $K(\tau)$ implies that $K'(\hat{\tau}_L) < \frac{K(\hat{\tau}_M) - K(\hat{\tau}_L)}{\hat{\tau}_M - \hat{\tau}_L}$ which can be rearranged to

$$K(\hat{\tau}_L) - K(\hat{\tau}_M) < \hat{\tau}_L K'(\hat{\tau}_L) - \hat{\tau}_M K'(\hat{\tau}_L) \tag{10}$$

Hence, G is strictly concave in p if for $p > 0$, the RHS of condition (10) is smaller than the RHS of (9), or $\hat{\tau}_M < 1$. This holds by condition (3) and the properties of $K(\tau)$.

(ii) To complete the proof, $G > 0$ must hold for small p. From above we know that $G(0) = 0$ and $G'(0) > 0$. The result follows immediately. ■

Proof of Proposition 1. It is straightforward to show that $F(\tau)$ exceeds $L(\tau)$ for $\tau \in [\hat{\tau}_F, 1[$ if $p < 1$. Thus, by Definitions 1 and 2 and uniqueness of p^* and p^{**} (see Lemmas 1 and 2), we know that $\forall \tau \in [\hat{\tau}_L, 1[\, L(\tau) - F(\tau) < 0$ if $0 < p < p^*$ and $\forall \tau \in [\hat{\tau}_F, 1[\, L(\tau) - F(\tau) < 0$ if $0 < p < p^{**}$. Hence, it needs to be shown that there is a unique equilibrium in pure strategies involving the leader's adoption at $\tau \in [\hat{\tau}_L, 1[$ if $0 < p < p^*$, and at $\tau \in [\hat{\tau}_F, 1[$ if $0 < p < p^{**}$.

First, suppose $0 < p < p^*$ and $\hat{\tau}_M$ is the global maximum of $L(\tau)$. The strategies that support the outcome specified in Proposition 1 are the following: firm i chooses 'Adoption' on $[\hat{\tau}_M, 1]$, given no previous adoption; otherwise it chooses 'Adoption' at $\tau_F{}^{opt}$ if the innovation is 'good'. Firm j chooses 'Adoption' at $\tau = 1$, given no previous adoption; otherwise it chooses 'Adoption' at $\hat{\tau}_F^{opt}$ if the innovation is 'good'. To see whether these strategies form a closed-loop equilibrium consider the subgames starting at $\tau \geqslant \hat{\tau}_M$, given no previous adoption. It is clear that no firm can gain by preempting before $\hat{\tau}_M$. Now suppose firm i deviates by not adopting at τ, but waiting an instant of time. Combined with firm j's strategy, firm i will still be the leader, only an instant later than τ. But since $\hat{\tau}_M$ maximizes $L(\tau)$, firm i is worse-off. By definition of $\tau_F{}^{opt}$, deviating makes firm j also worse-off. Thus, the proposed strategies form an equilibrium.

Next, if $0 < p < p^*$ and $\hat{\tau}_L$ is the global maximum of $L(\tau)$, the equilibrium strategies are identical to those given in the previous paragraph, except of the following specifications: $\hat{\tau}_M$ has to be replaced by $\hat{\tau}_L$, and firm i chooses 'No Adoption' during $\tau \in]\tau_R, \hat{\tau}_M[$, where $\tau_R \in]\hat{\tau}_L, \hat{\tau}_M[$ and $L(\tau_R) = L(\hat{\tau}_M)$. Any adoption date $\tau \in]\tau_R, \hat{\tau}_M[$ is dominated by $\hat{\tau}_M$. By the same arguments as used in the previous paragraph, these strategies implement the specified outcome and form a subgame perfect equilibrium.

Finally, if $0 < p < p^{**}$, the only possible pure strategy equilibrium outcome is that firm i $(=1,2)$ adopts at $\hat{\tau}_M$, and firm j $(\neq i)$ follows suit immediately if the innovation is 'good'. The strategies supporting this outcome are identical to those specified for the case when $0 < p < p^*$ and $\hat{\tau}_M$ is the global maximum of $L(\tau)$.

Clearly, the given strategies form a closed-loop equilibrium — up to relabelling of firms. To see that there are no other pure strategy equilibria, consider the case of $0 < p < p^{**}$. Suppose the strategies are those specified above for this case, but with $i = 1$ and $j = 2$ for $\tau < \tilde{\tau}$ and $i = 2$ and $j = 1$ for $\tau \geqslant \tilde{\tau}$, where $\tilde{\tau} \in]\hat{\tau}_M, 1[$. Hence, $F(\tilde{\tau}) > L(\tilde{\tau})$. Since $\tilde{\tau} > \hat{\tau}_M$ and L is continuous, it is possible to find a $\tau < \tilde{\tau}$ such that firm 1 prefers that firm 2 is the leader at $\tilde{\tau}$ (as prescribed by 2's strategy) rather than being itself the leader at τ, i.e. $L(\tau) < F(\tilde{\tau})$, but where firm 1's strategy prescribes 'Adoption', given no previous adoption. This is a contradiction. By similar arguments, it can be checked that there are no other equilibria in pure strategies for all cases of $p < \bar{p}$. ■

Proof of Proposition 2. If $p < p^{**}$ and $L(\hat{\tau}_L) > F(\hat{\tau}_L)$, one possible equilibrium outcome is that firm i $(=1,2)$ adopts at the earliest preemption date $\bar{\tau}(p)$ and firm j $(\neq i)$ at $\hat{\tau}_F$. As for the case of $p > \bar{p}$, this equilibrium is obtained by the application of Fudenberg and Tirole's argument. In this equilibrium, both firms receive $L(\bar{\tau}) = F(\bar{\tau})$. But since $p < p^{**}$, $L(\bar{\tau}) \leqslant L(\hat{\tau_L}) < L(\hat{\tau_M}) < F(\hat{\tau_M})$. Thus, both firms are better-off in the pure strategy equilibrium involving a follower advantage.

It is not difficult to show that there are other mixed strategy equilibria if $0 < p < \bar{p}$. For $0 < p < p^{**}$, the game is structured as a waiting game over the range $[\hat{\tau}_M, 1]$. In a mixed strategy equilibrium of a waiting game, at each instant, the payoff from adopting immediately and the payoff from waiting must be equal.

Because adopting immediately at the global maximum of $L(\tau)$ means $L(\hat{\tau}_M)$, each firm's expected payoff from any date on must be equal to $L(\hat{\tau}_M)$. Hence, the mixed strategy equilibria yield at most $L(\hat{\tau}_M)$ as ex-ante payoffs. Because one of the firms is strictly better-off in the respective pure strategy equilibrium and the other firm is equally well-off, the mixed strategy equilibria are Pareto-inferior. The same argument applies to the case when $p < p^*$ and $L(\tau)$ is having its global maximum at $\hat{\tau}_L$. In that case all mixed strategy equilibria yield at most $L(\hat{\tau}_L)$ and are therefore Pareto-dominated by the pure strategy equilibrium, which involves adoption at $\hat{\tau}_L$ and $\hat{\tau}_F$. ■

Proof of Propositions 4 and 5. From Section 3 we know that there are three different equilibrium outcomes depending on the probability that the innovation is profitable: (i) Firms adopt consecutively, but at same date $\hat{\tau}_M$ if $p \leqslant p^{**}$, (ii) sequentially at $\hat{\tau}_L$ and $\hat{\tau}_F$ if $p \leqslant p^*$ and $p > p^{**}$, and (iii) sequentially at $\bar{\tau}$ and $\hat{\tau}_F$ if $p > p^*$ and $p > p^{**}$. In the following, the three different equilibrium outcomes will be compared with the corresponding welfare-maximizing adoption dates. These are given by the following first-order conditions:

$$\frac{1}{r}\, p(\Pi_L + \Pi_F - 2\Pi_0 + C_1 - C_0) + K'(\tau_L^W) = 0 \tag{11}$$

$$\frac{1}{r}\,(2\Pi_2 - \Pi_L - \Pi_F + C_2 - C_1) + K'(\tau_F^W) = 0 \tag{12}$$

if $\tau_L^W < \tau_F^W$, and

$$\frac{1}{r}\, p(2\Pi_2 - 2\Pi_0 + C_2 - C_0) + (1+p)K'(\tau_M^W) = 0 \tag{13}$$

if $\tau_L^W = \tau_F^W = \tau_M^W$.

(i) It is easy to derive $\hat{\tau}_M > \hat{\tau}_M^W \; \forall p > 0$ from (3), (13), and the properties of $K(\tau)$. Thus, both firms adopting earlier increases W if $p \leqslant p^{**}$.

(ii) By conditions (1), (12) and the properties of $K(\tau)$, $\hat{\tau}_F < \hat{\tau}_F^W$ if $C_2 - C_1 < \Pi_L - \Pi_2$, which holds for all cases that satisfy condition (6). Similarly, by (2), (11) and the properties of $K(\tau)$, $\hat{\tau}_L > \hat{\tau}_L^W$ if $C_1 - C_0 > \Pi_0 - \Pi_F$, which holds again for all circumstances that satisfy condition (6). It follows that compared with the diffusion welfare maximum, the leader is too late and the follower too early if $p \leqslant p^*$ and $p > p^{**}$.

(iii) Taking the derivative of W with respect to τ_L at the point $\tau_L = \bar{\tau}$ yields that the earliest preemption date $\bar{\tau}$ is too early, optimal, or too late if $-\frac{1}{r}p(\Pi_L + \Pi_F - 2\Pi_0 + C_1 - C_0) - K'(\bar{\tau}) \gtreqless 0$. By taking (2) into account, this condition can be transformed in $K'(\bar{\tau}) - K'(\hat{\tau}_L) \lesseqgtr \frac{1}{r}p(\Pi_0 - \Pi_F) - \frac{1}{r}p(C_1 - C_0)$. In this equilibrium the follower adopts at $\hat{\tau}_F < \hat{\tau}_F^W$. This exhausts all possible equilibria that are not Pareto-dominated. ■

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