A STRATEGIC SEARCH MODEL OF TECHNOLOGY ADOPTION AND POLICY

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ABSTRACT

This chapter analyzes the link between adaptive R&D and the timing of new technology adoption in a strategic search model with heterogeneous firms. It is shown that the subgame-perfect equilibrium is in stopping rules with a reservation property. The model is used to examine the effect of rivalry, and whether R&D and adoption subsidies can increase social welfare and generate strategic advantage in international technological competition. It is found that the answers depend critically upon the relative magnitude of first-mover and second-mover advantages in the timing of adoption.

I. INTRODUCTION

One of the key determinants of industrial performance are the incentives to adopt cost-reducing new technologies and introduce new products in the marketplace. There exists a large literature on adoption and diffusion of new technologies (see Reinganum, 1989, and Karshenas & Stoneman, 1995, for a comprehensive survey). However, very little formal work has been done to explore the process of adaptation of new technologies to individual firms' requirements. The purpose of this chapter is to develop a formal framework that

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allows to study the link between adaptive R&D and the timing of new technology adoption. The analysis and insights of this model should provide some new answers to the questions of whether more competition may or may not force firms to improve and better exploit new technology, and how particular policy options may affect welfare and generate strategic advantage in international technological competition.

As Rosenberg (1976) notes, "it is an often-told tale in the history of inventions that they have to sit on shelves long after their initial conceptualization because of the absence of the appropriate mechanical skills, facilities, and design and engineering capacity required to translate them into a working reality" (p. 199). Imperfections in the new technology need to be overcome and bypassed by gradual inventive efforts. Modifications are required to meet the needs of the individual firms. Human skills have to be developed for an effective exploitation of the new technology. And often a series of complementary technological and organizational inventions has to be awaited before an innovation will appear attractive to potential adopters. Hence, the profitability of adopting a new technology may be increased by various development activities, however, these activities generally take time. Firms may therefore have an incentive to postpone the adoption of new technology until a later date. This incentive may be enhanced by late-mover advantages to adoption due to learning from the other firms' adoption experience (as in Hoppe, 2000), and offset by early-mover advantages because of strategic interaction in the product market (as in Fudenberg & Tirole, 1985). To find a firm's optimal adoption date these considerations have to be balanced.

The chapter presents a duopoly model in which firms may develop the profitability of adopting a new technology over time by active search for technological and adaptive information, taking potential first-mover and second-mover advantages into account. To accomplish this, I developed a strategic search model patterned after Chikte & Deshmukh (1993) and Lippman & Mamer (1993), but with important differences. In Lippman and Mamer's model, only one firm can adopt the new technology, i.e. the winner takes all. This chapter extends their model to allow for a follow-on adoption. Nevertheless, the first mover may be able to gain advantage for various reasons, e.g. better positioning in geographic and product characteristics space or preemptive investment in plant and equipment. However, second-mover advantages are likewise possible due to informational spillovers to adoption. In Chikte and Deshmukh's model of market entry and quality competition a second-mover advantage is not ruled out a priori. However, their analysis reveals that the competition always takes the form of a contest for being first.

In the model of the present chapter, firms employ reservation level strategies in the subgame-perfect equilibrium, i.e. they stop R&D and adopt the new technology if and only if the expected profitability of the new technology exceeds a certain level. At the equilibrium reservation level, the opportunity cost to delay – the risk of being preempted plus foregone earnings from the use of the new technology – are equal to the benefits of waiting – new information gained by active search or observing the adoption experience of other firms.

The analysis reveals that the firms' reaction functions in reservation levels slope upwards [downwards] when first-mover advantages are relatively more [less] important than second-mover advantages. This result may seem to contradict the findings by Gal-Or (1985) on the relationship between the slopes of reaction curves and the presence of first-mover and second-mover advantages. The explanation for the difference is that Gal-Or considers a two-stage game in which the order of moves is predetermined. In this chapter, the order of moves in the adoption game is made completely endogenous by adding a pre-play stage of search processes. The reaction curves considered in this chapter result from the decision in that pre-play stage.

The model is used to analyze the effects of rivalry on a firm's decision when to adopt a new technology. Contrary to Lippman & Mamer (1993), a firm's equilibrium threshold for the profitability of adopting first may be higher in a duopoly than a monopoly. This result is always obtained in the case of a strong second-mover advantage. The reason is that each firm's benefits from waiting for higher profitability are increased by the possibility that another firm may move first in the meantime. But even in markets with a strong first-mover advantage, a duopolist may choose to wait until it is more profitable to adopt the new technology, where a monopolist would have adopted. The reason is that the opportunity costs of waiting in terms of foregone profits are lower for a duopolist than a monopolist. This profit-dissipation effect is ruled out in Lippman and Mamer's model by the winner-take-all assumption.

The chapter also contributes to the surprisingly small literature on welfare issues and public policies with regard to adoption and diffusion of new technology.[1] The analysis reveals that R&D policies may influence the timing of adoption as well diffusion policies. In particular it is found that R&D and adoption subsidies differ in their impact on welfare, and should adequately depend on the relative magnitudes of early-mover and late-mover advantages in the timing of adoption. Furthermore, policy questions in the field of international technological competition are considered. In that context, R&D and adoption subsidies are shown to have opposing effects on the distribution of the leader's and follower's role.

This chapter bridges a gap between timing games and models of search. Search and game theory have been first combined by Reinganum (1982a) to analyze R&D competition. Since then, search processes have been more and more used to model development and information acquisition activities of competing firms (see, for instance, Reinganum, 1983, Mamer & McCardle, 1987, and Taylor, 1995). Nevertheless, to the best of my knowledge, only the following strategic search models allow for an analysis of timing questions: Chikte & Deshmukh (1993), Lippman & Mamer (1993), and Fershtman & Rubinstein (1997). However, all of them focus on first-mover advantages.

The chapter is related to the growing literature on real options or irreversible investment whose value stochastically evolves over time. However, in this literature the value of waiting is mostly analyzed in competitive settings without any externalities (see Dixit & Pindyck, 1994, for a survey).[2]

The model is set up in Section II. In Section III, the existence of closed-loop search equilibria is demonstrated. Comparative statics results and effects of rivalry are discussed in Section IV. Section V examines policy implications, and Section VI concludes. All proofs are placed in the appendix.

II. THE MODEL

There are two firms ($i = 1, 2$) contemplating to adopt a new technology. Each firm knows that, depending on the sequence of adoption, it may reap a potential first-mover or second-mover advantage of some sort. Apart from the adoption order, the expected value of adoption for a firm depends on how well the new technology fits in with the firm's working methods and production capabilities. This fit in turn is determined by the innovation's technical ambitiousness and the firm's competence in resource endowments and organizational capabilities (see the empirical study by Langowitz, 1988). Before adopting the new technology, each firm may therefore engage in adaptive R&D to enhance the fit and thus the profitability of adoption, e.g. by accumulating information from internal projects, technical consultants and academic research centers, exploring organizational innovations, training the labor force, and testing a prototype of the production process of a new good.[3] These activities generally involve time, costs and uncertainty. They are therefore best captured by sequential search processes (with recall). We assume that if a firm searches, it will obtain technological and adaptive information that is used to increase the (firm-specific) value of adoption over time.[4] The outcome of adaptive R&D is assumed to be private information.

Let $\Pi_1(n)$ and $\Pi_2(n)$ denote the value of the new technology for the first adopter (the leader) and second adopter (the follower), respectively, when n

firms have adopted the new technology. Assume further that $\Pi_2(2) = \alpha\Pi_1(2)$, where $\Pi_1(2) > 0, 0 \leq \alpha \leq 1$. Hence, we allow for a potential first-mover advantage of some sort.[5] Adoption involves a fixed cost of K_i for firm i, where $0 < K_i < \Pi_1(2)$. Adaptive R&D is assumed to result in a stochastic decrease of the adoption costs to $K_i - \theta$, or equivalently, a stochastic increase in the profitability of adoption by θ, where θ measures the value of the adaptive information, with $0 \leq \theta \leq K_i$. Confining the impact of R&D to the firm-specific value of adoption, i.e. ignoring any effects on the strategic advantage α, is restrictive but makes the analysis tractable. Moreover, this assumption enables us to link the search model to the timing game of new technology adoption by Fudenberg & Tirole (1985) in which technological progress is represented by an exogenous and deterministic decrease in the cost of adoption over time (see the discussion in Section III). θ is a random variable representable as a draw from a continuous distribution F_i defined on $[0, K_i]$, with non-negative density f_i everywhere on its domain and finite mean. The draws are mutually independent. New information from adaptive R&D is assumed to arrive according to a Poisson process with rate $\lambda > 0$. Let $r_i > 0$ be firm i's discount rate. Hence search is costly due to the opportunity cost of foregone earnings from the use of the new technology.[6] To rule out corner solutions, assume that a firm initially prefers to engage in adaptive R&D, i.e. that $\lambda\int_0^{K_i} \theta dF_i(\theta)$ is sufficiently high.

Apart from the active search for information, each firm may also passively acquire relevant information by observing the other firm's adoption experience. We assume that adoption by one firm gives rise to an informational spillover. Let ε_i denote the value for firm i of the information disclosed by j's adoption. For simplicity, assume, $\varepsilon_i = K_i - x_i$, where x_i is the increment to profitability developed at a given point in time. Hence, we consider the polar case, in which firm i learns the best way to adapt and adopt the new technology by observing j's experience such that further search activities become completely unattractive. The adoption problem reduces thereby to a two-stage problem, in which the order of moves is endogenously determined in the continuous-time game of adaptive R&D. This specification is extremely stylized, but it is sufficient to analyze the impact of differences in the adoption order on the firms' incentives to engage in adaptive R&D. We could specify other forms of potential second-mover and first-mover advantages, e.g. by introducing uncertainty, information lags, or allowing for a continuation of search activities by the follower and a temporary monopoly position for the leader. However, these details are not crucial for my purpose. The main point is that adoption is viewed as occurring sequentially, and in response to the outcome of adaptive R&D.

III. SUBGAME-PERFECT NASH EQUILIBRIUM

A strategy for each firm is a sequence of state-dependent decisions: when new information arrives, each firm decides whether to adopt or to wait until it becomes more profitable to adopt, contingent upon the increment to the value of adoption developed to date and the rivals' previous adoption decisions. I shall focus on subgame-perfect Nash equilibria in which the order of moves is not predetermined (subgame-perfect closed-loop equilibria). In the subgames in which one firm (the leader) has already adopted, the other firm's (the follower's) decision problem is solved by choosing a best response. Taking the follower's best response into account, we can solve for the equilibrium behavior in the subgames *prior* to the first adoption. For this, we need to find one firm's best response to the rival firm's strategy, given no previous adoption.

It is a well-known result from search theory for the case of an individual firm that a firm's optimal policy is to invest in adaptive R&D until x exceeds a reservation value ξ, such that

$$V^W(\xi) - V^A(\xi) = 0 \tag{1}$$

where $V^A(x)$ is the firm's expected payoff from adopting the new technology, given that the increment to profitability developed already is x, and $V^W(x)$ is the expected discounted payoff from an additional round of information acquisition activities (see for example McMillan & Rothschild, 1994). In the following it will be shown that each firm will employ such a reservation level strategy in the subgame-perfect equilibrium of the two-firm game. Lemma 1 will demonstrate that firm i's best response to a reservation level strategy of firm j, $\varphi_i(\xi_j)$, possesses the reservation level property, i.e. $\varphi_i(\xi_j) = \xi_i$, and is a continuous function. Lemma 2 will characterize the best response function further. Proposition 1 will then establish the existence of a subgame-perfect closed-loop equilibrium in reservation level strategies. Note that there cannot be any equilibria in which firms do not employ reservation-level strategies. This follows from Lemma 1 and the assumption that search is initially attractive for each firm.

Let $V_i^A(x_i, \xi_j)$ be firm i's expected return from adopting as a function of the highest x_i at hand and the rival's reservation level ξ_j, given that no firm has adopted previously. Hence,

$$V_i^A(x_i, \xi_j) = \Pi_1(2) - K_i + x_i, \tag{2}$$

Let $V_i^W(x_i, \xi_j)$ denote firm i's expected return from additional search activities, given no previous adoption. By waiting, firm i receives new information before firm j's adoption with probability $\lambda/[\lambda+\lambda(1-F_j(\xi_j))]$, but is preempted by firm j with probability $[\lambda(1-F_j(\xi_j))]/[\lambda+\lambda(1-F_j(\xi_j))]$. We know that in the simplest case of our model the follower's best response to the leader's adoption is immediate adoption. Hence, we have

$$V_i^W(x_i, \xi_j) = \frac{\lambda}{\lambda+\lambda[1-F_j(\xi_j)]+r_i}\,[\Pi_1(2) - K_i + \textstyle\int_{x_i}^{K_i} \theta dF_i(\theta) + x_i F_i(x_i)] + \frac{\lambda[1-F_j(\xi_j)]}{\lambda+\lambda[1-F_j(\xi_j)]+r_i}\,\Pi_2(2) \tag{3}$$

From Reinganum (1982a) we know that firm i's problem in the subgames prior to the first adoption is isomorphic to (1). Firm i's best response to ξ_j, $\varphi_i(\xi_j)$, is therefore an optimal stopping rule of the form: stop R&D whenever $x_i \geq \xi_i$, where ξ_i solves

$$V_i^W(\xi_i, \xi_j) - V_i^A(\xi_i, \xi_j) = 0; \tag{4}$$

otherwise continue. $\varphi_i(\xi_j)$ is obtained by substituting (2) and (3) into (4). To simplify notation, we define the value of the next round of adaptive R&D to be $H(x_i) \equiv \int_{x_i}^{K_i} (\theta - x_i) dF_i(\theta)$, and $\Pi \equiv \Pi_1(2)$.

Lemma 1. *(i) Firm i's best response to firm j's optimal stopping rule with a reservation level* ξ_j, *is to adopt whenever* $x_i \geq \xi_i$, *where* ξ_i *is the unique value such that*

$$\lambda H(\xi_i) = r_i(\Pi - K_i + \xi_i) + \lambda[1 - F_j(\xi_j)][(1-\alpha)\Pi - K_i + \xi_i]; \tag{5}$$

otherwise continue R&D. (ii) Firm i's best response function $\varphi_i(\xi_j):[0, K_j] \rightarrow [0, K_i]$ *is continuous in* ξ_j.

The LHS of equation (5) represents the value of the next piece of information, while the first term of the RHS is the opportunity cost in terms of foregone profits. The remaining term gives the impact of the rival firm's strategy. Depending on whether the potential first-mover advantage outweighs the potential second-mover advantage or vice versa, the existence of a rival increases either the marginal costs or benefits of waiting.

The following lemma relates the slopes of the reaction curves to the advantages in timing. This lemma may be of some independent interest, for it derives properties of reaction functions in reservation level strategies that are not restricted to the specific context analyzed in this chapter.

Lemma 2. *(i) For* $\alpha = 0$ *i.e. if there is a dominant potential first-mover advantage, each firm's reaction function slopes upwards. (ii) For* $\alpha = 1$*, i.e. if there is dominant potential second-mover advantage, each firm's reaction function slopes downwards.*

An upwards sloping reaction curve $\varphi_i(\xi_j)$ implies that an increase in the reservation level for the profitability of adoption by firm j induces firm i to undertake more development activity as well. The reason is that a higher value of ξ_j reduces the risk for i of being preempted by j in the case of potential first-mover advantages. By contrast, when potential second-mover advantages matter, a higher reservation level by j induces i to engage in less adaptive R&D. This is due to the smaller chance of benefiting from informational spillovers.

Proposition 1. *There exists a subgame-perfect Nash equilibrium in reservation level strategies* (ξ_i^*, ξ_j^*) *in* $[0, K_j] \times [0, K_i]$.

In this game, the equilibrium order of adoption is induced by chance due to the stochastic nature of the information acquisition process. Firms that are initially identical, will have an equal chance of being first or second in the adoption timing. This result resembles the finding of Fudenberg & Tirole (1985) for a timing game of new technology adoption in which adoption costs decrease deterministically over time. They show that the only subgame-perfect equilibrium is in mixed strategies, given that preemption gains are relatively large. With identical firms, each firm will be the leader with probability 1/2, and with probability 1/2 the roles of the firms are reversed – as in the present chapter. In fact, the stochastic nature of the search process replaces the need for mixed strategies in the present chapter.[7]

Another difference between the two models seems worth pointing out. In the model by Fudenberg and Tirole, the first adoption occurs immediately when the potential first-mover advantage outweighs any potential second-mover advantage. In the model of this chapter, however, there is a delay of the first adoption – even in the presence of a dominant potential first-mover advantage. The reason is that the stochastic nature of R&D generates an option value of waiting for new information for each firm. The risk of being preempted is therefore diminished. As a consequence, ex ante and ex post returns are equalized in Fudenberg and Tirole's adoption game, while there is an ex post first-mover advantage in the preemption equilibrium of the present chapter.[8]

IV. COMPARATIVE STATICS

As in the search model of Lippman & Mamer (1993), there may exist multiple equilibria. However, it can be shown that uniqueness is obtainable by assuming that the difference between the potential first-mover and second-mover advantage is not too high. I shall prove and state the following results for a unique (stable) equilibrium with $F_i = F_j$, $K_i = K_j$, and $r_i = r_j$.

Proposition 2. *An increase in the potential first-mover advantage, i.e. a decrease in α, leads to a new equilibrium in which both firms engage in less R&D. (ii) An increase in the potential second-mover advantage, i.e. an increase in α, leads to a new equilibrium in which both firms engage in more R&D.*

At a stable equilibrium, a higher advantage of moving first in the adoption stage induces firms to choose lower reservation levels in the R&D stage, while an increase in the potential second-mover advantages introduces the reverse incentives. Reinganum (1982b) obtains the opposite results in a patent race model. In her model, R&D efforts determine the hazard rate of the arrival of innovative information, and information is assumed to arrive only once. Conversely, in the model of the present chapter, the rate at which information arrives, λ, is assumed to be fixed, but firms may choose to engage in further information acquisition in order to increase the payoff from adoption. We may conclude that the net impact of the different forces stressed in each model upon the firms' incentives to engage in R&D is ambiguous.

Proposition 3. *(i) A decrease in r_i leads to a new equilibrium in which firm i undertakes more R&D, while firm j undertakes less [more] R&D if potential first-mover advantages are relatively less [more] important than potential second-mover advantages. (ii) A decrease in K_i leads to a new equilibrium in which firm i undertakes less R&D, while firm j undertakes more [less] R&D if potential first-mover advantages are relatively less [more] important than potential second-mover advantages.*

Proposition 3 shows that a firm's optimal reaction to a change in the rival's search and adoption costs is sensitive to the relative importance of first-mover and second-mover advantages. A decrease in r_i shifts up the reaction function of firm *i*, increasing both its own equilibrium reservation level and that of the firm *j*, provided the reaction functions are upwards-sloping. If the reaction functions are downwards sloping, firm *j*'s equilibrium reservation level is reduced. Conversely, a decrease in the cost of adoption K_i shifts firm *i*'s reaction function down. Thus we obtain exactly the opposite results.

The next proposition sheds further light on how firms' incentives to engage in R&D before adoption depend on the number of firms in the industry. Generally, one would expect that the following three effects matter. An additional competitor may lower the value of postponing adoption by increasing a firm's risk of being preempted (*the preemption effect*). On the other hand, it may enhance the value of waiting by increasing a firm's possibility of free-riding (*the information-spillover effect*) and by lowering a firm's opportunity costs of foregone profits due to increased competition in the product market (*the profit-dissipation effect*). The net effect of increased competition on adoption timing should hence be ambiguous. This ambiguity is reflected by the inconclusiveness of empirical research (e.g. a positive relation between market concentration and the speed of adoption is found by Hannan & McDowell, 1984, a negative relation by Levin et al., 1987, and no statistically significant one by Karshenas & Stoneman, 1993). In the theoretical literature, the issue is addressed by Lippman & Mamer (1993) who find that a firm's equilibrium reservation level for the value of adoption is decreasing in the number of potential adopters due to the preemption effect. In their model, only one firm is allowed to implement the new technology. This winner-take-all assumption eliminates both, the information-spillover effect and the profit-dissipation effect. By contrast, in situations with relatively more important potential late-mover advantages, the preemption effect is outweighed by the informational-spillover effect. An increase in the number of potential adopters would then increase a firm's reservation level for adoption.

The remaining question is hence whether the profit-dissipation effect can possibly outweigh the preemption effect in situations with relatively more important potential first-mover advantages. To see that this is possible, consider the case in which a firm is faced either by one competitor or by none. It is reasonable to assume that a monopolist does not make less profit than two non-colluding duopolists, i.e. $\Pi_1(1) \geq (1+\alpha)\Pi$. Let $\Pi_1(1) = A\Pi$, where $A \geq 1+\alpha$. The next proposition shows that under these circumstances the profit-dissipation effect may be greater than the preemption effect if the potential first-mover advantage is not too high.

Proposition 4. *Suppose there is no informational spillover to adoption. Then there exists a unique value of $\alpha \in [0, 1]$, denoted by $\hat{\alpha}$, such that a monopolist engages in less R&D than a duopolist if $\alpha > \hat{\alpha}$.*

V. POLICY IMPLICATIONS

In the following, particular policy options aimed at tuning the speed of adoption shall be examined (for an excellent survey of the diffusion policy literature and actual policy initiatives see Stoneman & Diederen, 1994). It will be shown that the policies of subsidizing R&D costs and subsidizing adoption costs are not equivalent, and that their effects depend crucially on the relative importance of first-mover and second-mover advantages.

V.1. Corrective Policies

The purpose of this subsection is to examine policies to correct for the negative externalities (business-stealing) and positive externalities (informational spillovers) in the firms' adoption behavior. For this, we will compare the equilibrium reservation level with that chosen optimally by a social planner whose objective is to maximize the firms' expected contribution to social welfare. Consumer surplus is hence neglected in our analysis in order to find Pigouvian corrective policies (as in Dixit, 1988). The next proposition reveals that, depending on the relative importance of first-mover and second-mover advantages, R&D subsidies or adoption subsidies may be used to deal with the externalities.

Proposition 5. *(i) If $\alpha = 0$, i.e. in the case of strong potential first-mover advantages, corrective policy takes the form of an R&D subsidy. (ii) If $\alpha = 1$, i.e. in the case of strong potential second-mover advantages, corrective policy takes the form of a subsidy of the adoption costs.*

Both policies, R&D and adoption subsidies influence the equilibrium timing of adoption by altering the marginal value of continuing search for technological and adaptive information. Subsidizing R&D reduces the marginal costs of search. This tends to delay technology adoption which is socially beneficial in the case of strong first-mover advantages. On the other hand, subsidizing adoption costs reduces the marginal saving from waiting in terms of interest earned. This tends to speed up adoption, and can therefore be used to correct positive externalities in the case of strong second-mover advantages.

V.2. Strategic Policies

The comparative static properties of the equilibrium reservation levels (Proposition 3) suggest that the firm-specific cost of R&D and adoption may be manipulated for strategic advantage. This issue may be particularly important in the context of international technological competition. In what follows, I consider a simple government policy, designed to put the domestic firm in the leader position when there are relatively more important first-mover advantages, and in the follower position otherwise. The purpose is to compare such a rent-seeking policy with the corrective policies derived above.

Assume that one firm is located in the home country and the other in the foreign country. The point of interest concerns the effects of R&D and adoption subsidies by one country on the distribution of the leader's and follower's role. The other country might, of course, responds to such a policy. For our purposes, we will ignore the strategic interaction between governments. The following proposition states that, in situations with relatively more important potential first-mover advantages, subsidizing the home firm's R&D will make the *foreign* firm more likely to be the first-mover, while subsidizing the home firm's adoption costs will make the *home* firm more likely to be the first-mover. The opposite result is obtained in the case of relatively more important potential second-mover advantages.

Proposition 6. *Consider a unique (stable) equilibrium with $F_i = F_j$, $K_i = K_j$, and $r_i = r_j$. A decrease in r_i [in K_i] makes firm i less [more] likely to reap potential first-mover advantages, and more [less] likely to reap potential second-mover advantages.*

The intuition behind this result is straightforward. The lower a firm's search costs, the higher its expected value of waiting for an additional piece of information. Hence, an R&D subsidy credibly reduces the home firm's threat of preempting its rival. On the other hand, a decrease in the adoption costs lowers the marginal saving from waiting, and thus credibly reduces the home firm's incentive to wait. What is perhaps surprising in these results is that the strategic policies tend to counteract the corrective policies.[9] In markets with strong potential first-mover advantages, an adoption subsidy would establish a strategic advantage in international competition. But the corrective policy for that country turns out to be an R&D subsidy. In markets with strong potential second-mover advantages, the opposite holds.

Apart from the policy implications, the comparative statics result of Proposition 6 contributes to the large (mainly empirical) literature focusing on how differences in firm-specific factors such as firm size, R&D expenditures, or firm ownership may determine the identity of the leader and follower firm (see Karshenas & Stoneman, 1995 for a survey). The result of Proposition 6 suggests that firms facing lower per-period R&D costs, for example, due to increasing returns to scale in information acquisition activities, would be expected to move later in the sequence of adoption, while firms with lower cost of adoption, for example, because of scale effects in marketing and distribution, would be expected to move earlier.

VI. CONCLUSIONS

This chapter has extended the strategic search models by Chikte & Deshmukh (1993) and Lippman & Mamer (1993) to allow for second-mover advantages to adoption. It has been demonstrated that the subgame-perfect equilibrium is in reservation level strategies. The slopes of the reaction functions in reservation levels have been shown to be determined by the relative importance of potential first-mover and second-mover advantages to adoption.

The model has been used to examine whether an increase in the number of potential adopters induces firms to expand or reduce adaptive R&D activities, and how R&D and adoption subsidies affect welfare and the determination of the identity of the first-mover. The analysis has revealed that the answers to these questions depend critically upon the relative magnitude of potential first-mover and second-mover advantages.

It seems worth further exploring the link between R&D and the timing of new technology adoption, as well as other options of technology policy.

NOTES

1. Exceptions are Stoneman & David (1986), Stoneman (1987), Jensen (1992), Riordan (1992), and Magnac & Verdier (1993).
2. An exception is Choi (1994) who considers a game-theoretic model of irreversible technology choice in which technologies stochastically evolve over time, but his focus is on network externalities.
3. That R&D activities play an important role in the process of adoption has been previously stressed by Cohen & Levinthal (1989).
4. One could alternatively model R&D as sequential search resulting in a resolution of uncertainty regarding the profitability of the new technology over time (see Jensen, 1982, for the one-firm context, and Bhattacharya et al. (1986) for a discussion of strategic interaction). Due to the underlying structural similarities between the two classes of search frameworks (see DeGroot, 1970, Section 13.9, Theorems 1 and 2), the results derived in this paper should also hold for the uncertainty resolution approach.
5. Examples are the Stackelberg equilibrium of a game of quantity competition or the Stackelberg equilibrium in a game of spatial competition (see Anderson & Engers, 1997).
6. Explicit search costs are neglected in this paper. Nevertheless, the main principles derived below should hold when such costs are included in the analysis.
7. See Proposition 6 for an analysis of how asymmetries between the firms define (stochastically) a particular order of adoption.
8. An ex post first-mover advantage in the preemption game of the Fudenberg & Tirole (1985) is also obtained by Hendricks (1992) by allowing for uncertainty about the innovative capabilities of the rival firm.
9. A similar observation is made by Dixit (1988) for a completely different model of R&D competition. See also Beath et al. (1989) for an examination of strategic R&D policies in international competition.

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APPENDIX

Proof of Lemma 1. The proof of this lemma is analogous to that of Lemma 1 in Chikte & Deshmukh (1993). Substituting (2) and (3) into (4) and rearranging terms yields equation (5). It is straightforward to show that the LHS of (5) is zero for $x_i = K_i$, and decreasing in x_i with slope $-\lambda[1 - F_i(x_i)]$. The RHS is smaller than the LHS for $x_i = 0$ (since corner solutions have been ruled out), non-negative for $x_i = K_i$, and increasing with slope $\lambda[1 - F_j(\xi_j)] + r_i$. Thus, by the continuity of $V_i^W(x_i, \xi_j) - V_i^A(x_i, \xi_j)$ on $[0, K_j] \times [0, K_i]$, there exists a unique value ξ_i such that $V_i^W(x_i, \xi_j) - V_i^A(x_i, \xi_j) \gtreqless 0$ as $x_i \lesseqgtr \xi_i$. Furthermore, continuity of $\varphi_i(\xi_j)$ on $[0, K_j]$ is ensured. ■

Proof of Lemma 2. By Lemma 1 and the implicit function theorem, firm i's reaction function $\varphi_i(\xi_j)$ is continuously differentiable with

$$\frac{\partial\varphi_i(\xi_j)}{\partial\xi_j} = -\frac{\partial(V_i^W - V_i^A)/\partial\xi_j}{\partial(V_i^W - V_i^A)/\partial\xi_i}. \tag{6}$$

For $\alpha = 0$,

$$\frac{\partial\varphi_i(\xi_j)}{\partial\xi_j} = \frac{\lambda F_j'(\xi_j)[\Pi - (K_i - \xi_i)]}{r_i + \lambda[1 - F_i(\xi_i)] + \lambda[1 - F_j(\xi_j)]} > 0 \tag{7}$$

For $\alpha = 1$,

$$\frac{\partial\varphi_i(\xi_j)}{\partial\xi_j} = -\frac{\lambda F_j'(\xi_j)(K_i - \xi_i)}{r_i + \lambda[1 - F_i(\xi_i)] + \lambda[1 - F_j(\xi_j)]} < 0 \tag{8}$$

The proof is analogous for firm j. ■

Proof of Proposition 1. Lemma 1 and application of standard fixed point arguments establish the existence of a Nash equilibrium. ■

Proof of Proposition 2. The comparative statics result is first derived for the reaction functions. At a stable equilibrium, the result can straightforwardly be extended to the equilibrium reservation levels.

By the implicit function theorem,

$$\frac{\partial\varphi_i(\xi_j)}{\partial\alpha} = \frac{\lambda[1 - F_j(\xi_j)]\Pi}{r_i + \lambda[1 - F_i(\xi_i)] + \lambda[1 - F_j(\xi_j)]} > 0 \tag{9}$$

The results for j are analogous. ■

Proof of Proposition 3. The comparative statics results are first derived for the reaction functions. At a stable equilibrium, the results can straightforwardly be extended to the equilibrium reservation levels.

By the implicit function theorem,

$$\text{(i)}\quad \frac{\partial\varphi_i(\xi_j)}{\partial r_i} = -\frac{\Pi - K_i + x_i}{r_i + \lambda[1 - F_i(\xi_i)] + \lambda[1 - F_j(\xi_j)]} < 0 \tag{10}$$

$$(ii)\quad \frac{\partial\varphi_i(\xi_j)}{\partial K_i} = \frac{r_i + \lambda[1 - F_j(\xi_j)]}{r_i + \lambda[1 - F_i(\xi_i)] + \lambda[1 - F_j(\xi_j)]} > 0 \tag{11}$$

and similarly for firm j. ■

Proof of Proposition 4. Consider a unique (stable) equilibrium with $F_i = F_j$, $K_i = K_j$, and $r_i = r_j$, and assume that there are no informational spillovers. If firm i is the only potential adopter it chooses a reservation level ξ_i^M, which solves

$$\lambda_i H(x_i) = r_i(A\Pi - K_i + x_i). \tag{12}$$

Comparing equations (12) and (5) yields, that $\xi_i^M < \xi_i^*$, if

$$r_i[A\Pi - K_i + x_i] > r_i(\Pi - K_i + x_i) + \lambda[1 - F_j(\xi_j^*)][(1 - \alpha)\Pi]$$

or

$$1 - \alpha < \frac{r_i(A - 1)}{\lambda[1 - F_j(\xi_j^*)]} \equiv 1 - \hat{\alpha}. \tag{13}$$

Since $A > 1$, $r_i > 0$, and $\lambda < 1$, it follows that $\hat{\alpha} < 1$. ■

Proof of Proposition 5. Consider a unique (stable) equilibrium with $F_i = F_j$, $K_i = K_j$, and $r_i = r_j$.

(i) Suppose $\alpha = 0$. Firm i's optimal reservation level ξ_i^* is the solution of

$$\lambda H(x_i) = r_i(\Pi - K_i + x_i) + \lambda[1 - F_j(\xi_j^*)](\Pi - K_i + x_i). \tag{14}$$

Given two independent R&D processes, the time until new information arrives is exponential with parameter 2λ. The social planner's optimal reservation level ξ_S is therefore the solution of

$$2\lambda H(x_i) = r_i(\Pi - K_i + x_i)$$

or

$$\lambda H(x_i) = r_i(\Pi - K_i + x_i)/2 \tag{15}$$

Since the RHS of (15) is strictly smaller than the RHS of (14) for all x_i, $\xi_i^* < \xi_S$. By Lemma 2 and Proposition 3, the result follows immediately.

(ii) Suppose $\alpha = 1$. Firm i's optimal reservation level ξ_i^* is the solution of

$$\lambda H(x_i) = r_i(\Pi - K_i + x_i) - \lambda[1 - F_j(\xi_j)](K_i - x_i) \tag{16}$$

The social planner's optimal reservation level ξ_S is the solution of

$$2\lambda H(x_i) = r_i(\Pi - K_i + x_i) + r_i\Pi \tag{17}$$

or

$$\lambda H(x_i) = r_i(2\Pi - K_i + x_i)/2 \tag{18}$$

Since the RHS of (18) is strictly greater than the RHS of (16) for all x_i, $\xi_i^* > \xi_S$. By Lemma 2 and Proposition 3, the result follows immediately. ■

Proof of Proposition 6. Firm i's adoption date is an exponentially distributed random variable with mean $E[T_{\xi_i^*}] = 1/[\lambda(1 - F_i(\xi_i^*))]$. Starting from a unique (stable) equilibrium with $F_i = F_j$, $K_i = K_j$, and $r_i = r_j$. we know from Proposition 3 that a decrease in r_i results in an increase of both firms' equilibrium reservation levels in the case of upwards sloping reaction curves. But the movement to the new equilibrium is along firm j's reaction curve. Thus $\xi_i^* > \xi_j^*$ in the new equilibrium. Likewise, if the reaction functions are downwards sloping, we have $\xi_i^* > \xi_j^*$ in the new equilibrium. Hence, in the new equilibrium, $E[T_{\xi_i^*}] = 1/[\lambda(1 - F_i(\xi^*{}_i))] > 1/[\lambda(1 - F_j(\xi_j^*))] = E[T^*_{\xi}]$. The proof for a decrease in K_i is similar. ■