NBER WORKING PAPER SERIES

BETTER LATE THAN EARLY: VERTICAL DIFFERENTIATION IN THE ADOPTION OF A NEW TECHNOLOGY

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Working Paper No. 4473

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
September 1993

We thank seminar audiences at Chicago, Rochester, Rutgers and the Game Theory Conference at Stonybrook as well as Ioannis Benopoulos, Andrew Caplin, Jay Pil Choi, Drew Fudenberg, Ananth Madhavan, Ariel Pakes, Suzanne Scotchmer and John Sutton for helpful comments. We have also benefitted from the comments of two anonymous referees and a co-editor. The usual disclaimer, unfortunately, applies. Any opinions expressed are those of the authors and not those of the National Bureau of Economic Research.

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ABSTRACT

After the initial breakthrough in the research phase of R&D a new product undergoes a process of change, improvement and adaptation to market conditions. We model the strategic behavior of firms in this development phase of R&D. We emphasize that a key dimension to this competition is the innovations that lead to product differentiation and quality improvement. In a duopoly model with a single adoption choice, we derive endogeneously the level and diversity of product innovations. We demonstrate the existence of equilibria in which one firm enters early with a low quality product while the other continues to develop the technology and eventually markets a high quality good. In such an equilibrium, no monopoly rent is dissipated and the later innovator makes more profits. Incumbent firms may well be the early innovators, contrary to the predictions of the "incumbency inertia" hypothesis.

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1. Introduction

An important characteristic concerning the innovation of a new product is that the initial research breakthrough is just a first step: after that breakthrough, the new technology can be further developed, improved and adapted to market conditions. At what point of this development stage does a firm adopt the new technology? For a monopoly, the trade-offs are clear: the longer it develops the innovation, the better the quality of the eventual product and the higher the subsequent flow profits but, of course, the more delayed the commencement of such returns.[1] In an oligopoly, how long any one firm waits to adopt the new technology will also be determined by the adoption decisions of other firms. The question of interest is: will competition lead to staggered innovations as early adopters market lower-quality products and later adopters wait to develop the technology further and then market higher-quality products?

In this paper we model the strategic behaviour of firms in the development stage as a process of vertical differentiation. Other papers that have examined the adoption of a new technology include Reinganum (1981), Fudenberg and Tirole (1985), Quirmbach (1986) and Katz and Shapiro (1987). The key difference between the current paper and that literature is that we model continuing innovations and improvements whereas in those papers the adoption of a newly discovered technology is almost always analyzed under the assumption that at the time of discovery, it is already in a form that can be marketed and undergoes no technical or economic modification afterwards. This difference in modelling motivates the following two questions.

If there is no room for differentiation after the first introduction, the crucial aspect of R&D activity becomes the race to be first in the discovery and introduction of a new product. As Fudenberg and Tirole (1985) showed, in such a model, to preempt the entry of other firms becomes the dominant feature of the development phase. Firms dissipate all intra-marginal rents which go to the first adopter, because any such profits to the first mover prompts a preemptive adoption by the others. Indeed endogeneous diffusion in adoption times emerges only if firms are able to precommit to their adoption decisions. The first objective of this paper is to examine the question: are staggered innovations likely when firms can improve a technology by waiting or does preemption remain the dominant feature of the adoption stage?

A second objective is to examine the "incumbency inertia" hypothesis: that a firm already in the market, or more generally the firm earning the highest flow profits under the old technology, will be less likely to adopt a new technology.[2] The intuition underying this hypothesis is simply that such a firm has the most to lose by way of cannibalization of its existing product and hence requires the incremental benefit of a new technology to be the highest before it switches. Note that if preemption is the dominant incentive of all firms then this issue cannot be meaningfully analyzed.

The model we consider is motivated directly by the adoption models of Reinganum (1981) and Fudenberg and Tirole (1985) and somewhat more indirectly by vertical differentiation models (for example, Shaked and Sutton (1982)). In our analysis we consider a duopoly. An idea or a new technology arrives exogenously into an industry, it is commonly available, and it can be improved by the two firms.[3] At any point of this development stage a firm can incorporate the currently available technology into a product and market it. The main conclusions of this model are:

Maturation and Rent Escalation There are two types of equilibria in the game. The first is the classic race outcome- a preemption equilibrium with rent equalization and dissipation. A second type of equilibrium appears with different return functions and other primitives. Here the unique[4] subgame perfect equilibrium induces *staggered innovations*: one firm, the leader, enters first with a low quality product and earns temporary monopoly rents, while the other continues to develop the technology and eventually markets a high quality product. We call this a *maturation equilibrium*. Interestingly, in such an equilibrium there is *rent escalation*: a later entry yields a higher lifetime profit (and there is no rent dissipation). In a parametric example we show that one underlying determinant of the type of equlibrium is consumer diversity: in this example, maturation equlibria exist if and only if there is sufficient diversity in preferences.

Incumbent Adopts First A natural conjecture for the staggered equilibrium is that an incumbent will innovate later. We argue that this conjecture overlooks a subtle signalling problem that multiple equilibria generate. Given rent escalation, each firm prefers the equilibrium in which it is the later adopter. However, precisely because of the cannibalization effect, the incumbent would pick a later entry date if it ended up as the low quality firm. This fact is common knowledge and gives the non incumbent the ability to make a credible commitment to be the high quality firm, by simply passing up its own best opportunity to be the first entrant.

The adoption and differentiation model is presented in Section 2 while Section 3 contains the discussion of preemption and maturation equilibria. The examination of incumbent incentives is in Section 4. Section 5 contains a brief discussion of extensions and further bibliography while Section 6 concludes.

2. The Innovation and Product Differentiation Problem

Consider a duopolistic market with firms indexed by a generic index, $i = 1,2$. j will index the "other" firm. Suppose the payoff relevant attributes of firm i's product can be represented by a single-dimensional variable: $x_i(t)$ is the level of technology or quality that is available to firm i at instant t. The quality level can be improved at a (common) constant rate, which we normalize to one. One may either imagine that this basic idea grows in a publicly accessible environment like a government or university laboratory or that it grows on account of the private activities of individual firms.[5] A firm's innovative activity is completely described by the decision on when to incorporate current quality and market its product. Each firm is allowed a single adoption choice.[6] Hence, in the sequel we shall sometimes refer to the latter, i.e. the adoption decision, as an innovation. The flow profits of a monopoly selling a product with attribute x will be denoted $R(x)$. If firm i has introduced a product with attribute x_i while j introduces a product at x_j, then flow profits to the duopolists from that point on depend on (x_i, x_j) and (x_j, x_i) respectively. These profits could be thought of, for example, as the returns to (one-shot) Cournot or Bertrand competition in the duopoly market.

We are aware that the model is simple but we believe that it is rich enough to examine our central intuition that quality competition shapes the nature of product development. In future work we would like to examine several generalizations; for instance, the possibility that the growth rate of quality is endogeneously determined by the firms. Of course, the models that have been studied in the standard homogeneous good framework are similarly simple and this allows a comparison of conclusions.

2.1 Assumptions

The principal simplifying assumption that we make is that duopoly returns depend only on the relative qualities, i.e.

(A1) Firm i's duopoly profits are given by a function, $r_i(x_i - x_j)$, $i = 1,2$, $i \neq j$

This assumption facilitates the analysis considerably: in Section 5 we discuss the consequences of relaxing it. From hereon we place a symmetry restriction on the duopoly profits, i.e. $r_i = r_j = r$, say. This assumption is relaxed in Section 4. Also denote $\theta = x_i - x_j$, the generic difference in qualities. The natural monotonicity assumptions are

(A2) i) Monopoly returns, $R(x)$ are increasing in x.
ii) In a duopoly, $r(\theta)$ is increasing in θ, whenever $\theta \geq 0$.

Whether a quality laggard makes more or less as θ increases, depends on the market's preferences over diversity. We make no assumptions hence on $r(\theta)$, for $\theta < 0$. Further, consider the following quasi-concavity and non-negativity assumptions:

(A3) i) $e^{-\delta x}[aR(x) + b]$ is strictly quasi-concave on R_+, for $a,b \in R_+$ and attains a maximum.
ii) $e^{-\delta\theta}r(\theta)$ is strictly quasi-concave on R_+ and attains a maximum.

(A4) r and R are non-negative and differentiable.

To complete the specification of the model, we have to specify what happens if both firms attempt to introduce a product at the same time. As is generally acknowledged, in continuous-time modelling there is no completely satisfactory way to treat simultaneous moves. We will make the following simplifying assumption:

(A5) If both i and j attempt to enter at any period t, then only one of them succeeds in doing so. The probability of firm 1 entering is $p \in (0,1)$.

Remark: Simultaneous adoption is hence ruled out although adoption at any $\tau > t$ is feasible. This assumption can be interpreted in at least two ways:

i) As a rationing rule induced by capacity or institutional constraints. For instance, if there is a common "adoption technology", like advertising, with limited capacity, the firm with first access to this technology is the one that successfully adopts. It can also be interpreted as an institutional feature such as a patent office which randomly selects one of the two adoption attempts.

ii) As a consequence of the belief that the decision to adopt cannot be carried out instantaneously. Suppose that if the decision to adopt is taken at time t, the adoption itself occurs at t+s, where s is an atomless random variable. (In this case the payoffs should be interpreted in an expected sense).[7] Here p should be interpreted as the probability of the event "firm 1's actual adoption occurs before that of firm 2."[8]

2.2 An Example

The strong assumption on returns is (A1). We present an example of Bertrand competition, adapted from the vertical differentiation model of Shaked and Sutton (1982) (as reported in Eaton-Lipsey (1989)) that satisfies (A1) (and additionally (A2) - (A4)).

Consumers have preferences on quality, with this preference index ranging over [a,b], $b > 2a > 0$. Each consumer has y units of a numeraire good and uses it to buy a single unit from either producer. The m-th consumer's utility from buying a good of vintage x_i is $mx_i + y - p_i$, $i = 1,2$, $m \in [a,b]$. Letting, without loss of generality, $x_1 > x_2$ (and writing $\theta = x_1 - x_2$ from now on), prices p_i yield market shares of $[a,\bar{m}]$ and $[\bar{m},b]$ where the high quality customers buy from firm 1 and the market divides at $\bar{m} = \frac{p_1 - p_2}{x_1 - x_2}$ $(p_1 > p_2)$. Straightforward computation yields prices (and profits) in Bertrand equilibrium as

$$p_1(\theta) = \frac{2b - a}{3}\theta \qquad p_2(\theta) = \frac{b - 2a}{3}\theta \tag{1}$$

$$r_1(\theta) = \left(\frac{2b - a}{3}\right)^2\theta, \quad r_2(-\theta) = \left(\frac{b - 2a}{3}\right)^2\theta, \qquad \theta \geq 0 \tag{2}$$

Symmetry gives the returns for $\theta < 0$. In this case it is easy to see that <u>both</u> r_1 and r_2 are increasing in θ, i.e. the more diverse the products the greater the profits for both the technological or quality leader as well as the laggard. This is of course the well-understood phenomenon of differentation lessening the severity of Bertrand price competition. Clearly (A1) - (A4) are satisfied in this example. Incidentally, it is also straightforward to show that the monopoly profits for a product of vintage x is

$$R(x) = \frac{b^2}{4}x \tag{3}$$

It depends only on the upper bound of consumer preference on quality, since a monopolist only services a fraction of the market optimally, and the choice is which of the high quality seeking customers to serve.[9]

2.3 Strategies and Equilibrium

A pure strategy of firm i, σ_i, specifies at any time t a decision on "adopt" or "do not adopt", if the firm has not adopted already. This decision is conditioned on the transpired history h_t, which is the knowledge: has j adopted at any $s < t$ and if yes, when. A strategy pair $\sigma = (\sigma_i,\sigma_j)$ associates with every history an outcome, a pair of adoption dates (t_i,t_j).[10] For instance if $t \leq t_i \leq t_j$, then writing $\theta = t_i - t_j$ (and hence $\theta < 0$), we get

$$W_i(h_t;\sigma) = e^{-\delta(t_i-t)} \left\{ (1 - e^{\delta\theta})R(t_i) + e^{\delta\theta}r(\theta) \right\}$$

$$W_j(h_t;\sigma) = e^{-\delta(t_i-t)} \left\{ e^{\delta\theta}r(-\theta) \right\}$$

The lifetime returns associated with other configuration of adoption times are easily computed. The equilibrium concept is that of subgame perfection: a strategy pair σ^* is an equilibrium if $W_i(h_t;\sigma^*) \geq W_i(h_t;\sigma_i,\sigma_j^*)$ for all other strategies σ_i and all histories h_t.

3. Pre-emption and Maturation Equilibria

Either of two equilibria can result in our product innovation model. The first, the classical pre-emption equilibrium (Fudenberg-Tirole 1985, Tirole 1989), arises from an inability by firms to sufficiently differentiate their products because of factors as market lock-in by a first entrant, a slow imitation technology or insufficient diversity of consumer preferences. Under alternative specifications of such primitives, a different, maturation, equilibrium obtains: competition results in an even flow of innovations. A potential technological leader optimally waits to develop a differentiated product. The other firm enters earlier to exploit a temporary monopoly position. None of the rent associated with this monopoly position is dissipated. However, an early entrant makes strictly less in equilibrium than the eventual quality leader. An early entrant cannot, in equilibrium, make strictly more (as Fudenberg and Tirole (1985) pointed out) but, given that time (or technology or quality development) is unidirectional, there is no inconsistency in its making strictly less: a first entrant cannot after all unilaterally decide to be the follower.

3.1 The Follower's Problem

Consider a continuation subgame after firm i adopts the technology at x. j's problem is to pick an optimal state $x + \theta$ at which to follow. In other words, j solves[11]

$$\max_{\theta \geq 0} \; e^{-\delta\theta}r(\theta) \qquad (4)$$

By (A3) ii), $e^{-\delta\theta}r(\theta)$ is single peaked on R_+. Let this peak occur at $\theta^* > 0$. It follows that firm j would follow at $x + \theta^*$. Hence, in any best response, all strategies prescribe: if the other firm has already moved, then move if and only if θ^* has elapsed since the competitor's adoption. Let F(x) denote the lifetime returns

$$F(x) = e^{-\delta x}\left\{e^{-\delta\theta^*}r(\theta^*)\right\} \equiv e^{-\delta x}\phi \qquad (5)$$

ϕ, the optimal returns to a follower's differentiation activities, is the direct index of differentiation possibilities in the market. ϕ is determined by underlying factors as diversity in consumer preferences, imitation or learning possibilities and market lock in.

3.2 The Leader's Problem

Following Fudenberg-Tirole (1985), we develop now the returns to a potential first entrant, or leader. Let L(x) denote the returns to a firm i, evaluated at date 0, if it innovates at quality x, anticipating an optimal follow by j at $x + \theta^*$.

$$L(x) = e^{-\delta x}\left\{(1 - e^{-\delta\theta^*})R(x) + e^{-\delta\theta^*}r(-\theta^*)\right\} \equiv e^{-\delta x}\left\{\lambda_1 R(x) + \lambda_2\right\} \qquad (6)$$

Any potential leader evaluates returns from two sources: $\lambda_1 R(x)$, the monopoly phase and λ_2, the phase in which it is a technological laggard in a duopoly. The effect of market differentiation possibilities on λ_k, k = 1,2 are more ambiguous than the effect on ϕ.

By (A3) i) L(x) is single-peaked. Further, note that $\frac{L(x)}{F(x)} = \frac{\lambda_1 R(x) + \lambda_2}{\phi}$, which is an increasing function of x. Hence, L and F have at most one intersection and suppose momentarily that there is in fact such an intersection. Denote this x^I and let x^M refer to argmax L. The two types of equilibria correspond to the two possibilities: a) $x^I < x^M$ and b) $x^I \geq x^M$.

(Figs. 1 and 2)

3.3 Equilibria:

Proposition 1 *a) **Preemption** Suppose that $x^I < x^M$ (figure 1). There is a unique pure strategy equilibrium to the development game. The associated outcome is:*

Both firms try to simultaneously adopt at x^I. Firm 1 (resp.2) adopts with probability p (resp. 1-p) and the remaining firm adopts at $x^I + \theta^*$.

The strategies that support this equilibrium are the following: firms i and j try to innovate at all dates after x^I if neither has innovated before that date. If i has innovated already, j innovates iff θ^* has elapsed since i's innovation.

*b) **Maturation** Suppose that $x^I \geq x^M$ (figure 2). There is a unique pure strategy equilibrium. The associated equilibrium outcome is:*

firm i unilaterally adopts at x^M and j follows at $x^M + \theta^*$.

The strategies that support this equlibrium are the following: firm i tries to innovate at all dates after x^M while j tries to innovate at all dates after x^I, if neither has innovated till that date. If i has innovated already, j innovates iff θ^* has elapsed since i's innovation. There are two asymmetric equilibria for i=1,2.

Proof: Since the proof of a) is contained in that of b), we start with the latter. We first show that the strategies outlined form a subgame perfect equilibrium. Given j's strategy, i solves the following problem at any x in $[0,x^I)$: (if it has not adopted already)

$$\max_{x^I \geq z \geq x} \; e^{-\delta(z-x)} [\lambda_1 R(z) + \lambda_2]$$

Clearly the solution is x^M if $x \leq x^M$ and x if $x > x^M$. So if j does not adopt till x^I, i's best response is to adopt at any date after x^M, if it has not adopted yet. Moreover for all x in $[x^M,x^I)$, $L(x) < F(x)$ and hence j has no incentive to preempt i's adoption. It is further clear that if the game was ever at $x \geq x^I$, a dominant strategy for either firm is to move immediately (recall (A5): if both try to move, nature selects the actual entrant). So the exhibited strategies in fact form a subgame perfect equilibrium.

Now consider any pure strategy equilibrium. Clearly, for any $x < x^M$, waiting and adopting at any later $x' < x^M$ dominates an immediate adoption. We now show that it cannot be the case that there is $x_i < x_j$, $x_i, x_j \in [x^M, x^I)$, with i adopting at x_i and j adopting at x_j (in each case if the other has not adopted till that point). For some $x_1 < x_j$, $F(x_j) > L(x)$, $x \in (x_1, x_j)$. So if i anticipates following at x_j, waiting to follow at x_j is more profitable than adopting at any $x \in (x_1,x_j)$. But then, if firm i is going to wait till x_j, it is better for j to adopt immediately at any $x \in (x_1,x_j)$, rather than wait till x_j. So in fact j moves at x_1 if neither has moved till that point. In turn, there is $x_i < x_2 < x_1$ such that for any $x \in (x_2, x_1)$, i's preferred strategy is to wait and consequently j's is to immediately lead. It is clear that a finite iteration of this logic in fact works back to x_i.[12] But then, i should not be moving at x_i. In other words, there can only be one leader in equilibrium. Finally consider $x \geq x^I$. In this region adopting if neither has adopted before is a dominant strategy. Hence equilibrium strategies are necessarily the given strategies.

The exhibited strategies are the only equilibrium strategies in case a) as well. Clearly, for any $x < x^I$, waiting and adopting at any later $x' < x^I$ dominates an immediate adoption. Consider any history starting at $x > x^I$. It cannot be the case that only one of the two players adopts at x. In fact, since the profit from a joint move is at this point strictly larger than $F(x)$, it is better for the other player to attempt to adopt as well. On the other hand it cannot be the case that the outcome adoption time is some $x' > x$, with, say firm j being one of the adopters, (and possibly the only one). This cannot be an equilibrium since firm i is better off being the sole adopter at some $x'' < x'$. •[13]

Remark 1 From the arguments above it is clear that the "no simultaneous move" assumption, (A5), can be replaced by a requirement that there are equilibria in subgames starting at x^I which result in payoffs no more than $L(x^I) = F(x^I)$.

Remark 2 Consider the adoption of a (homogeneous) technology. If the fixed cost of adoption is unchanged over time (we have in fact normalized it to zero), then $\theta^* = 0$ and hence $x^I = 0$. Consequently the only possibility is that of preemption. In Shaked-Sutton (1982), and other vertical differentiation models, there exist asymmetric equilibria (like our maturation possibility) but there is no dynamic story for their emergence.

We shall say (see Tirole (1989)) that rents are (partially) dissipated if the first adopter does not realize the returns that it would get if it had proprietary rights on first adoption , i.e. if in an equilibrium the first adoption is $x \neq x^M$.

Corollary 2 *In a pre-emption equilibrium, rents are equalized and this is achieved through a dissipation of rent. In a maturation equilibrium a follower makes strictly higher profits, although a leader realises the full monopoly rent.*

3.4 An Illustrative Example

We compute equilibria in the Shaked and Sutton model to illustrate how consumer diversity determines whether the equilibrium is of the preemption or maturation type. Recall that in this model (Example 2.1) consumer preference for quality (which scales the utility function) is uniformly distributed on [a,b], $0 < a < b$. We define an increase in diversity as a decrease in a, keeping b fixed (since a change in b has an additional scale effect as well). It can be shown that

$$L(x) = e^{-\delta x}\left\{\frac{(1 - e^{-1})b^2}{4} x + (\delta e)^{-1}\left(\frac{b - 2a}{3}\right)^2\right\} \equiv e^{-\delta x}\left\{\lambda_1 x + \lambda_2(a)\right\}$$

$$F(x) = e^{-\delta x}(\delta e)^{-1}\left(\frac{2b - a}{3}\right)^2 \equiv e^{-\delta x}\,\phi(a) \qquad (7)$$

It is easy to show that we have a maturation (resp. preemption) equilibrium if and only if $\frac{a}{b} < \xi$ (resp. $\frac{a}{b} > \xi$)where ξ is a positive constant independent of the primitives of the model.[14] It is also clear from (7) that as diversity increases, a potential leader would like to innovate earlier, i.e. $x^M(a)$ is an increasing function of a. This follows directly from the fact that not adopting has a higher waiting cost, the postponement of greater duopoly returns $\lambda_2(a)$.

4. Entrants Versus Incumbents

In this section we examine the incumbency inertia hypothesis: incumbent firms are less likely to be innovators in new product development.[15] There are at least two reasons why we investigate this hypothesis in some detail. Incumbency, as we define it here, is one way to incorporate asymmetry between firms in an industry and it is a good proxy in many cases to differences in size or experience. The question that interests us is whether or not such asymmetries can identify uniquely the order of adoption (and of course whether the order is that suggested by the hypothesis). Further although this hypothesis has been widely investigated in many different contexts and models (for example, see Arrow (1962), Gilbert and Newbery (1982), Reinganum (1983) as also the excellent summary in Tirole (1989)), a number of these investigations were in essentially static models.

The main result of this section shows that although incumbents prefer postponing innovations, in equilibrium they may be unable to do so precisely because they are known to have this preference. An incumbent is a firm which is in the relevant market at period 0 and making some instantaneous profits $\pi > 0$. These profits disappear upon the adoption of the new technology. The size of the current profits π is then a measure of incumbent inertia. Our principal finding (Proposition 3) is that there is a critical level of profits, say $\hat{\pi}$, above which the non-incumbent (entrant) does adopt first (and makes lower lifetime profits). However, for $\pi < \hat{\pi}$ a forward induction argument suggests that in fact an incumbent is the first to adopt. The intuition for this result is the following: suppose that the firms are unaware which of two equilibria (incumbent high-quality or entrant high-quality) is being played. However it is common knowledge that if the entrant were to be the low-quality firm it would only develop the product till date T (whereas the incumbent, if it were low-quality, on account of cannibalization likes to wait till a later date). If date T passes and there is no new product on the market, forward induction logic suggests that the only reasonable conclusion that the incumbent can reach is that the potential entrant plans on being the high-quality (second-adopter) firm in the industry. Hence the incumbent maximizes its returns by adopting earlier and making lower profits. The implication of forward induction that we invoke is the one suggested by van Damme (1987, 1989) (see also Fudenberg and Tirole (1991), pp. 464, Definition 11.8, which we report): "A solution concept S is *consistent with forward induction in the class of generic two-person extensive forms* if there is no equilibrium in S such that some player i, by deviating at a node along the equilibrium path, can ensure (with probability one) that a proper subgame G is reached where (according to S) all solutions but one give the player strictly less than the equilibrium, and where exactly one solution gives the player strictly more."

From hereon, let firm 1 refer to the incumbent and firm 2 to the entrant. Then, between period 0 and the first adoption x, firm 1 makes a flow profit $\delta\pi$ (and firm 2, the entrant, makes nothing). So,

$$F_1(x) = (1 - e^{-\delta x})\pi + F(x) \tag{8}$$
$$L_1(x) = (1 - e^{-\delta x})\pi + L(x)$$

Of course, $F_2 = F$ and $L_2 = L$.

(Fig. 3)

Proposition 3 *Suppose the symmetric game had a maturation equilibrium. Then there is a a unique forward induction proof equilibrium and a critical level of incumbent profit $\hat{\pi} > 0$ such that:*

i) for $\pi \leq \hat{\pi}$, the outcome is: incumbent adopts at x_1^M and the entrant follows at $x_1^M + \theta^*$.

ii) for $\pi > \hat{\pi}$, the equilibrium outcome is: entrant adopts at x_2^M and the incumbent follows at $x_2^M + \theta^*$.

If the symmetric game had a pre-emption equilibrium, then so does the asymmetric game with an outcome:

probabilistic move by firm i at x^I, j follows at $x^I + \theta^*$.

Proof: It is immediate, from (8), that x_i^I, the intersection of F_i and L_i, are identical for both firms. Let us maintain the notation for this common intersection point and call it x^I. Further, precisely because adopting a new product means foregoing current profits π, if firm 1 <u>had</u> to lead it would lead later than firm 2 in a similar situation, i.e. $x_1^M > x_2^M$. Note that in terms of our earlier notation, $x_2^M = x^M$ and we use the notation interchangeably. It should be easy to see that any increase in π increases x_1^M (i.e. increases incumbency inertia) and leaves x^I and x^M unchanged.

Suppose now that the symmetric game had a maturation equilibrium, i.e. that $x^I >$

x^M. We have two cases to consider:

Case 1: $L(x^M) \leq F(x_1^M)$: By arguments identical to those in Proposition 1 one can show that there are only two subgame perfect equilibria. The first has the entrant moving at all $x \geq x_2^M$, if the other firm has not moved yet while the incumbent (firm 1) only adopts at $x \geq x^I$ if neither has adopted till such point. Of course, as a follower each follows after the optimal gap of θ^*. Beyond x^I both firms will try to adopt if neither has adopted till that point. The second equilibria has the roles reversed with firm 1 (the incumbent) leading at x_1^M, and firm 2 only adopting (together with firm 1) after x^I. Since $L(x_2^M) \leq F(x_1^M)$, the entrant would rather follow at x_1^M, than lead at x_2^M. In fact because of this preference, the forward induction implication of van Damme (1987, 1989) (reported above) will now be used to show that only the second of the two equilibria survives that refinement.

Suppose in fact that the first equilibrium is consistent with the refinement. Suppose further that the subgame we are in is that starting at x_2^M. Firm 2 can now deviate from the proposed strategy by not adopting at x_2^M (and adopting instead at $x' \in (x_2^M, x_1^M)$). This deviation by firm 2 takes us into a subgame with two equilibria. In the first, firm 2 adopts immediately and receives as payoff $L(x')$ while in the second it waits for firm 1 to adopt at x_1^M and gets $F(x_2^M)$. But $L(x') < L(x_2^M) < F(x_1^M)$ contradicting the above necessary condition for forward induction. Note that firm 1 cannot credibly signal before 2's adoption date precisely because the cannibalization factor means it is strictly better off not innovating early.

Case 2: $L(x^M) > F(x_1^M)$: It is not difficult to see that there are two subgame perfect equilibria in this case. The first is identical to the first equilibrium in case 1 with the entrant leading at x^M. Define x^* through $L(x^*) = F(x_1^M)$. The second equilibrium is: firm 2 adopts for all x in $[x^M, x^*]$ or $x \geq x^I$, if neither has adopted before, whereas firm 1 adopts for all $x \geq x_1^M$. An argument identical to that for case 1 but applied now to the region $[x^*, x_1^M)$ shows that only the second equilibrium is consistent with forward induction. Of course, the outcome in either case is: the entrant adopts at x^M and the incumbent follows at $x^M + \theta^*$.

Since x_1^M is increasing (and hence $F(x_1^M)$ is decreasing) in incumbent profit π, there is a critical profit level $\hat{\pi}$ which divides the two cases above and below which the entrant can credibly signal his unwillingness to lead and force the incumbent, despite the cannibalization effect, into a leadership position. For $\pi \geq \hat{\pi}$, the cannibalization effect dominates. Finally note that if the symmetric game had a preemption equilibrium, i.e. if $x^I < x^M$, then $x^I < x_1^M$ and hence the only equilibrium is one in which both firms try to adopt after x^I. •

An alternative notion of incumbency advantage can also be defined. We will call this indirect incumbency and we will now discuss briefly its consequences. An indirect incumbent is a firm which may not be in the precise market under consideration but has better information about it, perhaps by virtue of selling similar products. As an index of indirect incumbency advantage we shall maintain that the incumbent makes higher profits: an incumbent makes $m_1 R$, $m_1 \geq 1$, as a monopolist, whereas an entrant only makes R (as before) and it makes $m_2 r$ as a duopolist, $m_2 \geq 1$, whereas an entrant only makes r (as before). Denote $m = m_1/m_2$. We show (Proposition 4) that for any $m > 1$, the unique equilibrium is one in which the incumbent necessarily adopts first. The reasoning is as follows: monopoly rents are higher for the indirect incumbent and consequently the date at which it prefers to adopt rather than be a follower is earlier for such a firm. A backward induction argument then establishes the result.[16] We have

$$L_1(x) = e^{-\delta x}\left\{(1 - e^{-\delta\theta^*})m_1 R(x) + m_2 e^{-\delta\theta^*} r(-\theta^*)\right\} \qquad (9)$$
$$F_1(x) = m_2 F(x)$$

For expositional purposes, in this sub-section we assume $r(-\theta^*) = 0$. The reader can check that none of the results are predicated on this; it merely makes the presentation a lot clearer since in this case $L_1(x) = m_1 L(x)$ and consequently $x_1^M = x_2^M$. We maintain notation and call this common maximum x^M. Of course, $L_2 = L$, $F_2 = F$. Clearly, starting from a maturation equilibrium in the symmetric game, we have figure 4.

(Fig. 4)

Proposition 4 *Suppose that $m \geq 1$. Suppose also that the symmetric game has a maturation equilibrium. Then, there is some critical incumbency advantage $\hat{m}$ s.t.*

i) for $m < \hat{m}$, the unique equilibrium has incumbent adopting at x^M, the entrant at $x^M + \theta^*$. No rent is dissipated but the entrant makes strictly more in equilibrium.

ii) for $m \geq \hat{m}$, the unique equilibrium has the same outcome as above, but the *incumbency advantage is sufficiently big to overwhelm the first mover disadvantage. The incumbent makes more.*

Finally, if the symmetric equilibrium is a pre-emption equilibrium, then so is the asymmetric with the outcome:

incumbent adopts at x^I and entrant follows at $x^I + \theta^*$.

Proof: See Appendix 2. •[17]

Remark Propositions 3 and 4 illustrate the usefulness of a dynamic formulation of a vertical differentiation problem. In standard formulations as Prescott-Visscher (1977) or Shaked-Sutton (1982) (see also the survey of such models in Eaton-Lipsey (1989)), quality choices are essentially made in a static model: they are chosen in stage one prior to price competition in stage two. Consequently neither the forward nor backward induction arguments made above can be applied. Even in asymmetric versions of such games typically both of the outcomes contained in the maturation possibility remain equilibrium outcomes. By contrast we have shown that some kinds of asymmetry, no matter how small, can uniquely identify particular equilibrium outcomes.

5. Extensions and Other Research

The principal assumption which facilitated the analysis is (A1), that duopoly returns depend only on relative qualities. Dropping this assumption complicates the analysis but, in a qualitative sense, leaves the main intuition and results unchanged. Note that if duopoly returns depend on the quality levels of both products, then the optimal amount of product differentiation engaged in by a follower will depend on the level of the first innovation. Denote this dependence $\theta(x)$. The principal complication arises from not knowing, in general, qualitative features of this function.

Yet, in two senses, the current analysis generalizes. First, it is clear that the critical properties driving all of our results are that the follower and leader payoffs, F and L, are, respectively, decreasing and single-peaked. These properties are consistent with duopoly profits that depend on the quality levels of both products, under appropriate restrictions. Second, even if F and L do not inherit these properties, there may be several equilibria but it is still the case that all of them are of the maturation or pre-emption type. The general analysis for this class of games may be found in Dutta and Rustichini (1993).

The controversial element of our formulation is our simplification that firms do all of the development before adoption and adopt only once. We can allow limited "learning by doing", i.e. we can let a product in the market continue to be exogeneously improved. This generalization can be straightforwardly incorporated into our formulation provided the rate of improvement prior to an introduction (in the laboratory) is greater than the rate of improvement after the introduction (in the market).

A second generalization is more difficult and that relates to repeat innovations. Repeat innovations are an important stylised fact of the innovative process. Indeed, this issue has been discussed in a number of recent papers; see Grossman and Helpman (1991a, 1991b), Aghion and Howitt (1992) and Segerstrom, Anant and Dinopolos (1991). These papers, although they provide valuable insight into the innovation process, share a critical common feature with the Reinganum (1981), Fudenberg and Tirole (1985), Quirmbach (1986) and Katz and Shapiro (1987) papers that we have tried to innovate on in this current work. This common feature is that all inventions come "ready-made" and do not undergo any further improvements; in the repeat innovations papers there are, of course, many such inventions. Hence, whenever a discovery is made it is immediately adopted. Our central concern in this paper has been with inventions that can be further improved and our interest is in the question of how much of improvements are actually made.

It would clearly be interesting to put the waiting and improving considerations into a repeated framework, as well. One aspect of this problem has been modelled in Dutta-Rustichini (1990a), although we are far from a good understanding of the overall process.

We have already discussed the preemption and rent equalization result of Fudenberg and Tirole (1985).[18] Reinganum (1981) showed that, given precommitment possibilities, there would be a diffusion of adoption times if the fixed costs of adoption decline over time. These papers, as well as related work by Quirmbach (1986) and Katz and Shapiro (1987) of course consider a homogeneous good model in which the initial technology cannot be subsequently improved.

8. Conclusions

In this paper we argued that an important determinant of the decision of a firm on when to adopt a new technology is how much and how quickly future improvement of this technology is likely to occur. In an oligopoly an additional, strategic determinant is a firm's expectations of the timing of other firms' adoption. We studied these decisions as a process of vertical differentiation and demonstrated equilibria in which firms emerge with products of different qualities. In such diffusion of a new technology late adopters make strictly higher profits. We suggested that incumbents may be unable to delay their adoption decisions since they are known to have a preference for doing so.

As a more general point we believe that it is important to recognize that the same initial technological breakthrough can be developed in many different directions. In this manner firms are able to compete around patents. This suggests that the organization of research as well as its intensity is likely to be determined by the extent of competition in the post-breakthrough development phase, i.e.that the adoption dynamics of a breakthrough will influence the conduct of the research phase of R&D. We hope to investigate in the future issues as the attractiveness of RJVs and optimal patent policies in just such a framework.

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Appendix 1

In this appendix we formally construct a sequence of discrete time games whose equilibrium outcomes have the equilibrium outcomes of our continuous time game as a limit. For any $h > 0$ consider a set of discrete time periods, $t = h, 2h, \ldots$ and define a family of games G_h: at each of the time periods either player can choose an action from the set $\{0,1\}$ (corresponding to "do not adopt" or "attempt to adopt" respectively). If only one player chooses 1, the adoption is successful whereas if both players choose 1, then player 1 adopts with an exogeneously given probability p and player 2 adopts with probability 1-p. The growth of quality level and the flow payoffs are identical to the symmetric continuous time model (and assumptions (A2)-(A4) are maintained). For any pair of adoption dates, t_i and t_j we define the lifetime payoffs as in Section 2.3, with the obvious restriction that the quality levels have to be on the time-grid

A strategy for player i maps any history, which in our game is summarized by the knowledge: has j adopted and if yes when, into the action set. Of course, if i has already adopted, then his action is identically 1 thereafter. To every pair of strategies there is an associated outcome which specifies the first and second adoption dates (or quality levels).

The payoffs to optimally following, which we denote F_h, is defined in the obvious way (see (4)). It is easy to see that the optimal lag in the discretised problem, say $\theta^*(h)$, is within h of the optimal lag, θ^*, in the continuous time model. The payoffs to the first adopter, conditional on an optimal action of the follower, will be denoted L_h.[19] It is also easy to see that F_h and L_h converge uniformly to F and L, as $h \to 0$.

We now show the following convergence result:

Lemma The set of equilibrium outcomes of the games G_h converge to the unique, preemption or maturation, equilibrium outcome of the continuous time game.

Proof: For simplicity, we consider only the maturation case, $x^I > x^M$. Associated with G are the analogs, $x^I(h)$ and $x^M(h)$ (and for small h, $x^I(h) > x^M(h)$). Define a strategy pair for the discrete game as follows: player 1 plays action 1 if neither player has adopted and $x \geq x^M(h)$. Player 2 plays action 1 if neither player has adopted and $x \geq x^I(h)$. As a follower, each player adopts with the optimal lag of $\theta^*(h)$.

Since F_h and L_h converge uniformly to F and L, they inherit the properties of the latter two functions for small h. In particular, L_h is strictly increasing (resp. decreasing) for $x \leq x^M(h)$ (resp. $x \geq x^M(h)$) and F_h is strictly decreasing. From these properties, it is straightforward to see that the above pair of strategies constitutes a subgame perfect equilibrium in the game (with associated outcome $x^M(h)$, $x^M(h)+\theta^*(h)$). Hence, the set of equilibrium outcomes in G_h is nonempty.

We now demonstrate the fact that the set of equilibrium outcomes converges to x^M, $x^M + \theta^*$ as $h \to 0$. It evidently suffices to show that any sequence of equilibrium first adoption times converges to x^M. Suppose, to the contrary, that we have a sequence of equilibrium first adoption times converging to $x' \neq x^M$. If $x' > x^M$, it is easy to show that, for small h, at least one player is strictly better off by adopting at the period before the first adoption date. If $x' < x^M$, then, for small h, waiting one period and then adopting dominates immediate adoption at the candidate first adoption date.

The proof is similar for the preemption case.•

Notice that the construction above is not specific to the symmetric game. Indeed, the asymmetric continuous time game can be discretised in an analogous fashion. Moreover, the lemma on equilibrium outcome convergence holds in this asymmetric game approximation as well.

Appendix 2

Proof of Proposition 4: Suspose the symmetric game has a maturation equilibrium. Note that on account of the indirect incumbency advantage $x_1^I < x_2^I$ and indeed x_1^I is decreasing in m. This of course just says that the opportunity cost of the incumbent for staying out of the market is higher than that of the entrant and this cost is increasing in mt. Clearly, in any equilibrium, a dominant strategy for firm 1 is to adopt beyond x_1^I if neither has adopted before. But then, there is $x^1 < x_1^I$ such that adoption is a dominated strategy for 2 at any $x \in [x^1, x_1^I)$. x^1 is formally defined through

$$x^1 = \max \left\{ z\colon L(x) \leq F(x_1^I) \quad x \geq z \right\} \tag{A.1}$$

In the figure, $x^1 = 0$. More generally, there is some left neighborhood of x_1^I, in which firm 2 does better by waiting to follow, than by leading. Given this, firm 1's dominant strategy is to lead on $[x^1, x_1^I)$. An identical argument as in Proposition 1 now leads through an iterated elimination of dominated strategies to: firm 1 adopts at x^M (and any time thereafter). The entrant, firm 2 follows at $x^M + q^*$. Note, despite the incumbency advantage, the entrant makes strictly more than the incumbent. As $m\uparrow$, x_1^I decreases and hence at some critical advantage $\hat{m}$, $x_1^I = x^M$. Clearly, for any $m \geq \hat{m}$, the equilibrium outcome is incumbent moves at x^M and makes more than the entrant.•

Addendum

In this addendum we discuss the case where duopoly profits depend on quality levels and comment on the precise sense in which the results of the current paper, in which the profits depend only on the difference in qualities, generalize. The arguments draw from the enclosed paper that two of us wrote, "A Theory of Stopping Time Games with Applications to Product Innovations and Asset Sales" (hereafter DR). The reason for not including this discussion in the text is our belief that too much of a background discussion of our other paper would be required in order to do a complete job. Hence this exercise, which is only intended for the referees' eyes.

In DR we considered a general class of stopping games which are defined as follows: either of two players can, at any instant, "stop" a (possibly multi-dimensional) stochastic process $\{X(t): t \geq 0\}$. If the process is stopped by player i at time t, then his payoffs are $l(X(t)$ whereas those of player j are $f(X(t))$; these functions are only required to be continuous. Simultaneous moves result in a payoff to player 1 (resp. 2) of $pl(X(t) + (1-p)f(X(t))$, (resp. $pf(X(t) + (1-p)l(X(t)))$, p in $(0,1)$.

Within this class of games, first introduced by Bensoussan and Friedman (1977) and evidently a more general framework than the adoption game studied in this paper, we studied *stopping equilibria*. In the adoption game, these are equilibria in the following strategies: player j only adopts beyond x^I, if neither player has adopted before. Player i solves the following maximization problem at all $x \leq x^I$: $\max e^{-\delta(x'-x)} l(x')$, $x' \in [x,x^I]$ and stops at all x at which the solution to the problem is x itself (and also stops beyond x^I, in both cases if j has not adopted already). When the maximum in the above problem is realized at x^I, we have a preemption equilibrium whereas if the maximum is at $x < x^I$ we have a maturation equilibrium (and there may be several of these). We showed (Propositions 3-4 in DR) that <u>all</u> subgame perfect equilibrium outcomes in a game of timing (like the adoption game) are generated by stopping equilibria.

It is also worth noting that, in any case, all of our results in the current paper were driven by the fact that the functions F and L are, respectively, decreasing and single-peaked. These properties while straightforward to derive in the difference-dependent profits case, are evidently not limited to this case. In this sense even our exact results are not limited to this specification of the duopoly profit function.

[1] For instance, in commenting on the possibilility that a new technology may be further improved, Rosenberg (1982, p.108) remarks: "In their earliest stages, innovations are often highly imperfect and known to be so. ... If one anticipates significant improvements, it may be foolish to undertake the innovation now - the more so the greater the size of the financial commitment." Rosenberg also documents many historical instances of gradual adoption of a new technology. Indeed, the optimal time to "stop" and adopt the available technology is the instant at which the marginal benefit to waiting, the expected improvement in profits, is exactly equal to the discounted cost of profits foregone for another instant.

[2] For example, Schumpeter (1934) says, "...it is not essential to the matter--though it may happen--that the new combinations should be carried out by the same people who control the productive or commercial process which is to be displaced by the new. On the contrary, new combinations are, as a rule, embodied, as it were, in new firms which generally do not arise out of the old ones but start producing beside them." This phenomenon was called by Arrow the "replacement effect" (see Tirole (1989) pp 392-396 for a very instructive discussion and Reinganum (1983) for a result on incumbency inertia in patent races). In what follows we have in mind what Tirole calls "drastic innovation", i.e. one which replaces the old technology.

[3] In contrast, in Reinganum (1981) and Fudenberg and Tirole (1985), technology remains unchaged over time although the cost of adopting it declines monotonically.

[4] The equilibrium is unique up to a permutation in the labelling of the firms.

[5] The growth rate of quality is in general stochastic and firm-specific but in the current model we abstract from these considerations - see Section 7 for further comments.

[6] Repeat innovations, although empirically of great importance, bring up a set of issues tangential to the main questions of interest in this paper. See, however, Section 5 for a further discussion.

[7] In this case there is an issue as to whether the decision to adopt is reversible once the other firm is observed to have adopted the new technology. The analogy is exact if the adoption decision is reversible.

[8] Note that (A5) is equivalent to an assumption that allows "public randomization" by the firms. The reader can verify that our results will remain unaltered under the alternative assumption that the two firms can adopt simultaneously and their payoffs, if they do so, are a convex combination of the payoffs to the leader and follower.

[9] In Dutta, Lach and Rustichini (1990) we also give an example of Cournot duopolists, with imperfectly substitutable products, whose returns satisfy (A1)-(A4).

[10] It is well known that continuous time game strategies in which sudden moves are possible, as in the innovation game, may fail to have well-defined outcomes associated with them. All of the anomalies stem from the fact that "instantaneous" reactions are typically admissible in such games but there is no instant after. A sufficient condition to have well-defined outcomes is the requirement that all strategies σ satisfy $\limsup_{t \to t^*} \sigma(h_t) \leq \sigma(h_{t^*})$ (writing $\sigma(h_t)=1$ (resp. 0) for "adopt" (resp. "not adopt")). As Section 3 will show, the fact that firm j cannot react instantaneously to firm i's adoption is not a restriction in a best response. That firm j cannot react instantaneously to i's non-adoption (i.e. that strategies of the form "j adopts the first instant after t if i has not adopted till that point" are not allowed) is a restriction but arguably a non-critical one.

[11] Note that flow returns were normalized to $\delta r(\theta)$, so the infinite horizon discounted returns are $r(\theta)$.

[12] Else, there is an accumulation point $x < x^I$, s.t. $F(x) = L(x)$.

[13] The remaining two possible configurations are: $L \geq F$ always. The equilibrium then is trivial: each firm attempts to move at every instant. The outcome is probabilistic entry by i at 0 and an optimal follow by j at θ^*. Conversely, $F \geq L$ throughout. The equilibrium strategies are: i moves at all $x \geq x^M$, j never moves if i has not moved before. The outcome is the rent preserving one of x^M, $x^M + \theta^*$. These two trivial equilibria are of course special versions of pre-emption and maturation equilibria respectively. From hereon we supress discussion of these trivial cases.

[14] In fact $\xi = 2 - \frac{3}{2}\left[\delta e\left(1 - \frac{1}{c}\right)\right]^{\frac{1}{2}}$.

[15] It is worth reiterating that we only consider a drastic innovation. When an innovation is not drastic, i.e. the profits of a product employing the old technology are not driven to zero upon the entry of a product embodying the new technology, incumbents may well innovate first. (See Tirole (1989), pp. 346-348 for an example).

[16] The intuition is similar to that driving the Ghemawat-Nalebuff (1986) result that in a declining industry the larger firm may be the first to exit.

[17] If $m < 1$, then the entrant is the first firm to adopt. The arguments in this case are exactly the reverse of those in the proof of Proposition 4.

[18] Fudenberg-Tirole also showed that for some specification of returns in their model there might be a continuum of joint adoption equilibria which do not involve a race but do result in rent equalization and (in all except one equilibrium) rent dissipation.

[19] The functions F_h and L_h are extended to the real line by linear interpolation.

Figure 1

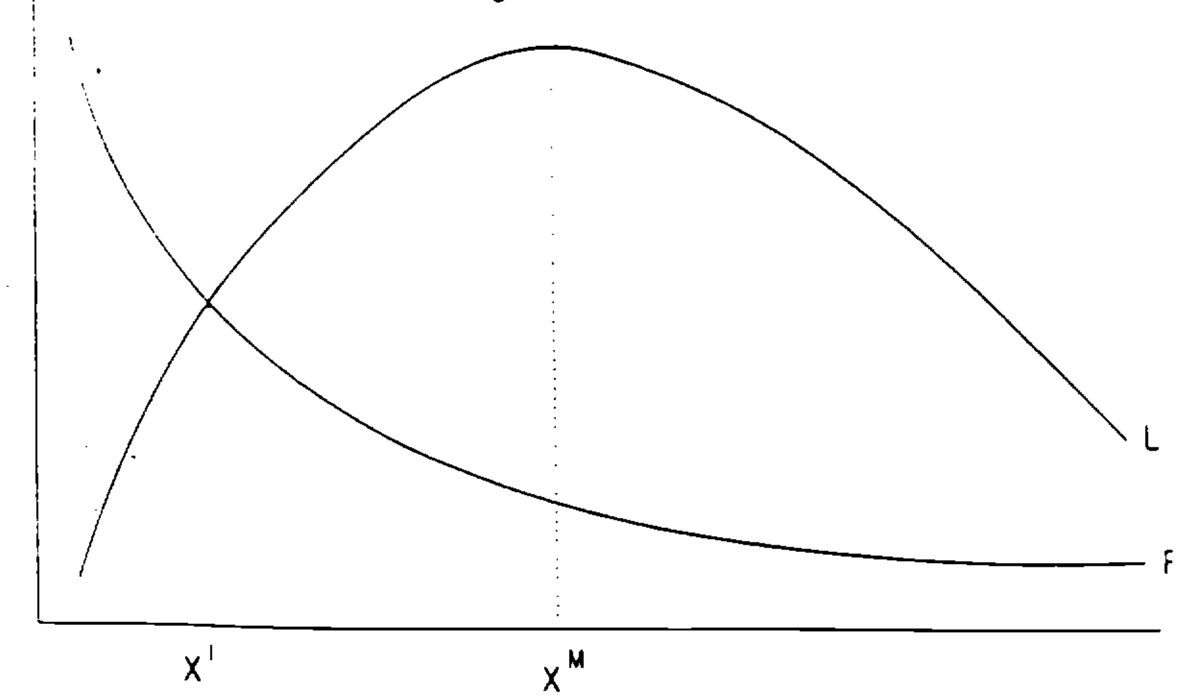

Figure 2

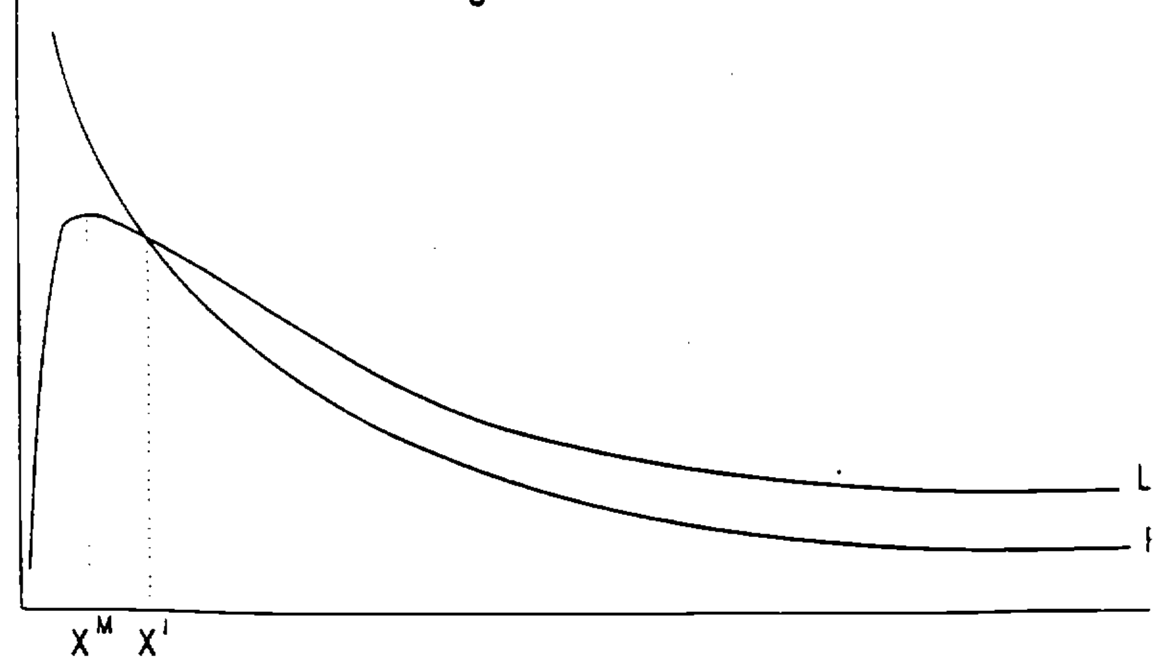

Figure 3

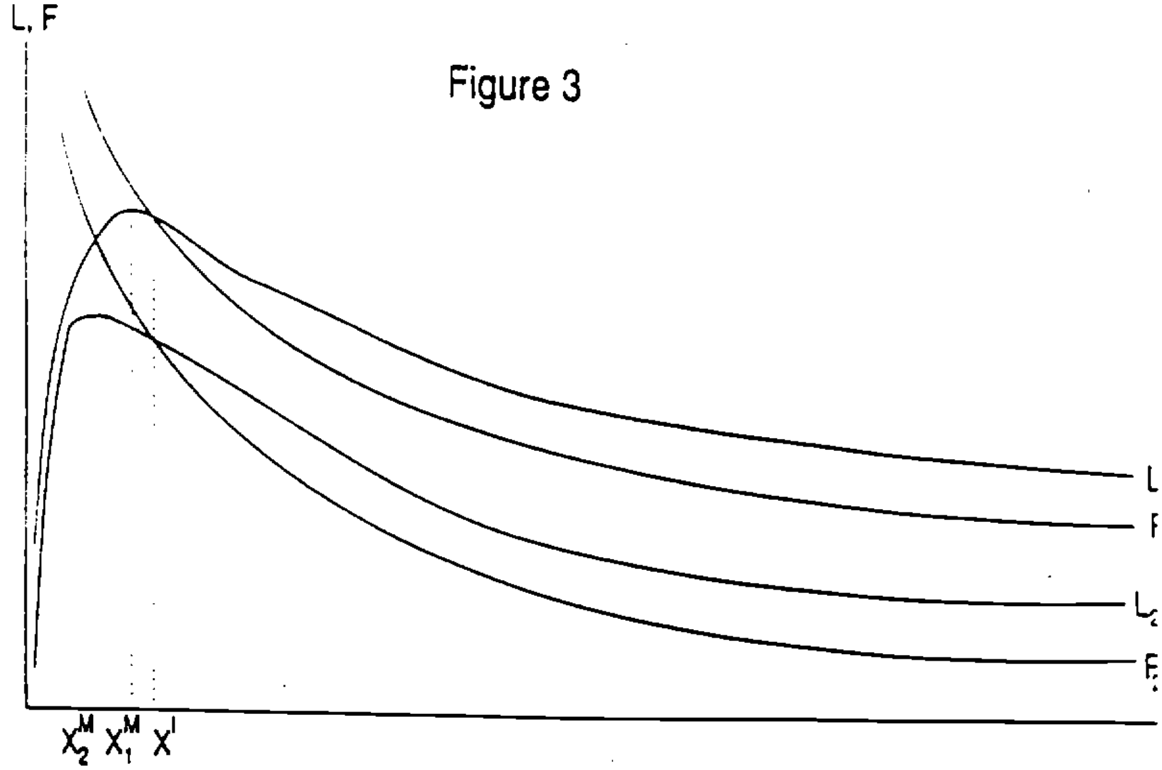

Figure 4