PRODUCT INNOVATION AND PERSISTENCE OF LEADERSHIP: THEORY WITH EVIDENCE FROM THE SEMICONDUCTOR INDUSTRY

by

Harald Gruber
London School of Economics and Political Science

The Toyota Centre
Suntory and Toyota International Centres for
Economics and Related Disciplines
London School of Economics and Political Science
Houghton Street
London WC2A 2AE
Tel.: (020) 7955 6674

Discussion Paper
No. EI/2
June 1990

I would like to thank *Ente L. Einaudi (Rome)* for financial support and John Sutton for helpful discussion during the various stages of the work. Useful suggestions to an earlier draft by participants at workshops at CEPR and STICERD are also acknowledged. Any remaining errors are, of course, mine.

Abstract

This paper sets out to model the evolution of market shares in the semiconductor industry. The time profile of market shares for different firms in this industry has shown a striking regularity over successive generations of products. In a model of vertical product differentiation three distinct patterns of market shares emerge as an equilibrium outcome, reflecting three distinct strategies in respect of timing of entry into new generations. The main novelty of the model developed here, relative to the existing literature on vertical product differentiation, lies in the incorporation of *learning by doing*.

Keywords: Vertical product differentiation; semiconductor industry; 'learning by doing'; market shares; time profile.

1. INTRODUCTION AND SUMMARY

This paper sets out to model the evolution of market shares in the semiconductor industry. The time profile of market shares for different firms in this industry has shown a striking regularity over the past fifteen years. This pattern reflects the fact that firms in this industry follow one of three distinct strategies over time in respect of their timing of entry into each new generation of products. These strategies are respectively: to enter early; to "follow the leader" after some lapse of time; or to enter late. These three strategies are reflected in the differing profiles of a firm's market share over time. The first strategy is associated with a market share that begins from unity and falls monotonically; the second with a share profile which first rises and then falls; and the third with a monotonically rising share profile.

The aim of this paper is to construct a model which is consistent with the basic facts observed in the memory chip industry. In the model these three distinct patterns of market shares emerge as an equilibrium outcome. The model developed here is a modified version of the vertical product differentiation model of Shaked and Sutton (1982,1987). The model appears to conform well to several regularities observed in the data presented below. The basic assumption which drives these results relates to *"learning by doing"* effects. Firm specific *learning by doing* plays a major role in determining the cost of production of memory chips. In the production process a certain number of chips on a silicon "wafer" must be discarded because of defects. Semiconductor production therefore entails a considerable "waste" of silicon, and this wasting is highest in the early stage of the product life cycle. One cost of beginning production of a new generation of products may be identified with the total wastage incurred over a relatively short 15-18 month period from the date of entry. This time span is so short that wastage can be modelled as a fixed cost. The main novelty of the model developed here, relative to the existing literature on vertical product differentiation, lies in the incorporation of these fixed costs, which are interpreted as a (very rapid) *learning by doing* effect.

This paper is organised as follows. Section 2 presents empirical evidence from the semiconductor industry by focussing on the market for memory chips such as EPROMs (Erasable Programmable Read Only Memories). These have the ideal properties of vertically differentiated products and, in its production, learning plays knowingly an extensive role. It is shown that the world market share of the US firm Intel, the inventor of memory chips, has a pattern which shows a remarkable stability over various generations. This pattern is similar to that implied by the "leader" in the theoretical model. Similarly, the world market shares of the US firms Texas Instruments and AMD closely follow the patterns identified by the entry strategies of the "follower" and the "late entrant" respectively. Section 3 refers to the literature and defines the basic concepts used in the present approach. Section

4 lays out the static version of the three firms vertical product differentiation model. Having three firms allows for a richer range of innovation patterns than in a duopoly. In section 5 the framework is extended to a dynamic game in order to analyse the adoption process. The role of the *learning by doing* assumption is emphasised. Section 6 draws a conclusion and suggests possible extensions.

2. EMPIRICAL EVIDENCE FROM THE SEMICONDUCTOR INDUSTRY

This section sets out some stylized facts regarding the semiconductor industry. The memory chip product line has shown very high growth rates over the last 20 years. Memory chips are designed for the storage and retrieval of information in binary form. A type of nonvolatile memory chip, i.e. which does not lose memory content once power is switched off, is the Erasable Programmable Read Only Memory (EPROM)[1] where the memory content can be reprogrammed by particular procedures. Memory chips are classified into "generations" according to their storage capacity in terms of Binary Information Units (BITs). A 16k EPROM has a memory capacity of about 16000 bits.

---

1 The source of data on EPROMs is Dataquest. The data is on worldwide annual shipments of each firm for each generation of chips. Prices are average selling prices.

Technical progress is characterized by increasing memory capacity per chip. In the case of EPROMs this has been translated into doubling of memory capacity from one generation to the next. The product basically remains the same all the time, only its performance has been increasing over time.

Taking memory capacity as a characteristic of quality, increases in memory capacity may be seen as quality improvement of the product. Furthermore, memory devices are highly standardized products. Most devices of the same memory capacities made by different firms are easily substitutable[2]. Furthermore there is intergenerational substitutability in the sense that two 8k EPROMs do more or less the same job of one 16k EPROM.

A remarkable characteristic of EPROMs, and semiconductor devices in general, is the strong and regular price fall for chips of a given generation. At the beginning of the product cycle of a given generation the price is very high. But it falls quickly to the level where it becomes competitive with the previous generation in terms of per bit price. For a 16k EPROM to compete effectively with a 8k EPROM it is sufficient for the price not to be higher than twice that of the 8k device. The sales cycle of a given generation is typically hill-shaped wherby the peak increases from generation to generation.

---

2 Users of memory chips require the availability of at least one alternative supplier, or "second source", as a precondition for the adoption of a certain device.

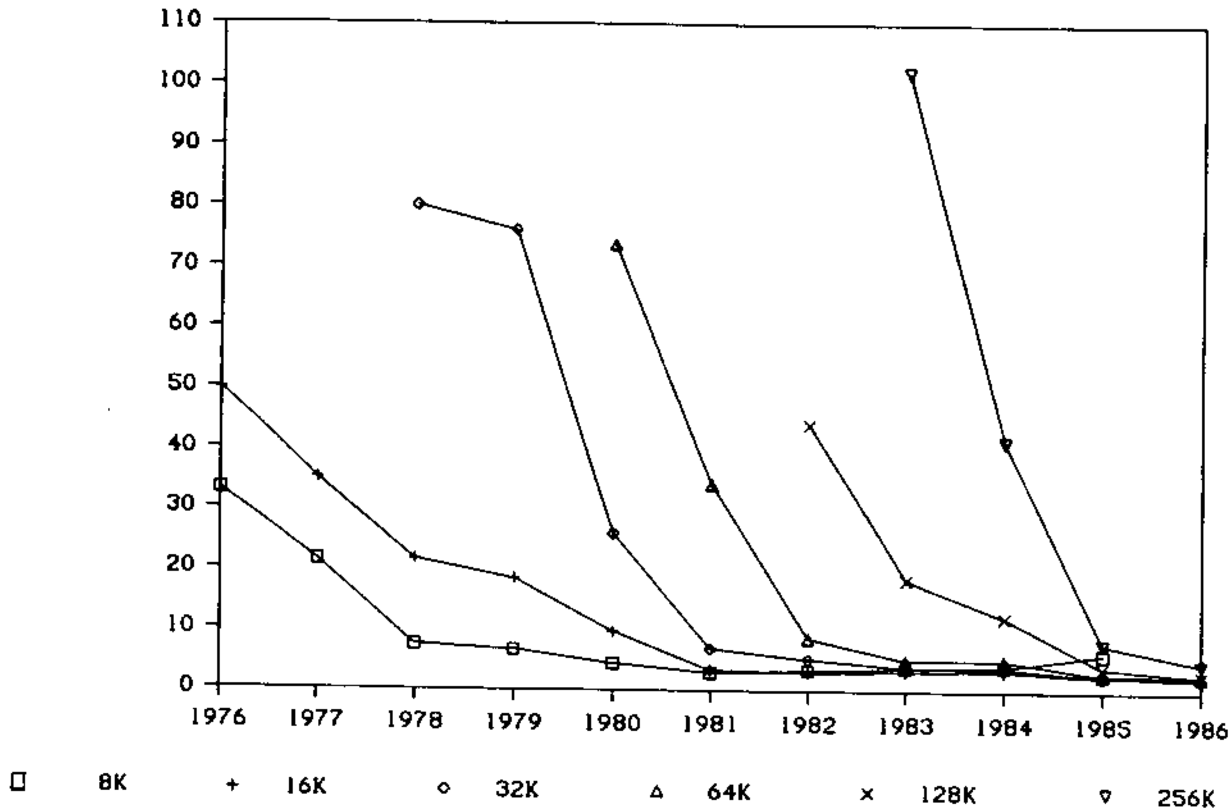
Tecnical progress is very predictable. There is the so-called *Moore's law*, after one of the founders of Intel, which claims that memory capacity doubles each 15 months.

Learning in production seems to be one of the main features in production of semiconductors. Semiconductor production is a batch process which involves considerable waste of silicon due to defective chips on the "wafer" in paricular during the early stage of production. This waste is typically reduced over time through learning. The production yield, i.e. the ratio of usable chip to total chips per batch, increases with production experience. Since product cycles of a generation of EPROMs are very short, the sum of discarded silicon over time may be treated as fixed cost representing the cost of supplying a higher density generation.

This learning is mostly firm specific and can partially be carried over to the next generation. Thus there is a spillover in the production ability from one generation to the other. To be able to compete effectively in the production of a given generation one has to have produced already the previous generation.

As far as firms are concerned we have some remarkable facts. Intel, the US producer who actually invented the memory chip and maintains a reputation for its innovative ability, is the typical dominant producer at the beginning of the generational cycle. This is translated into initially high and then decreasing

Diagram 1. The market share pattern of the innovative leader <u>Intel</u> for different generations of EPROMs.

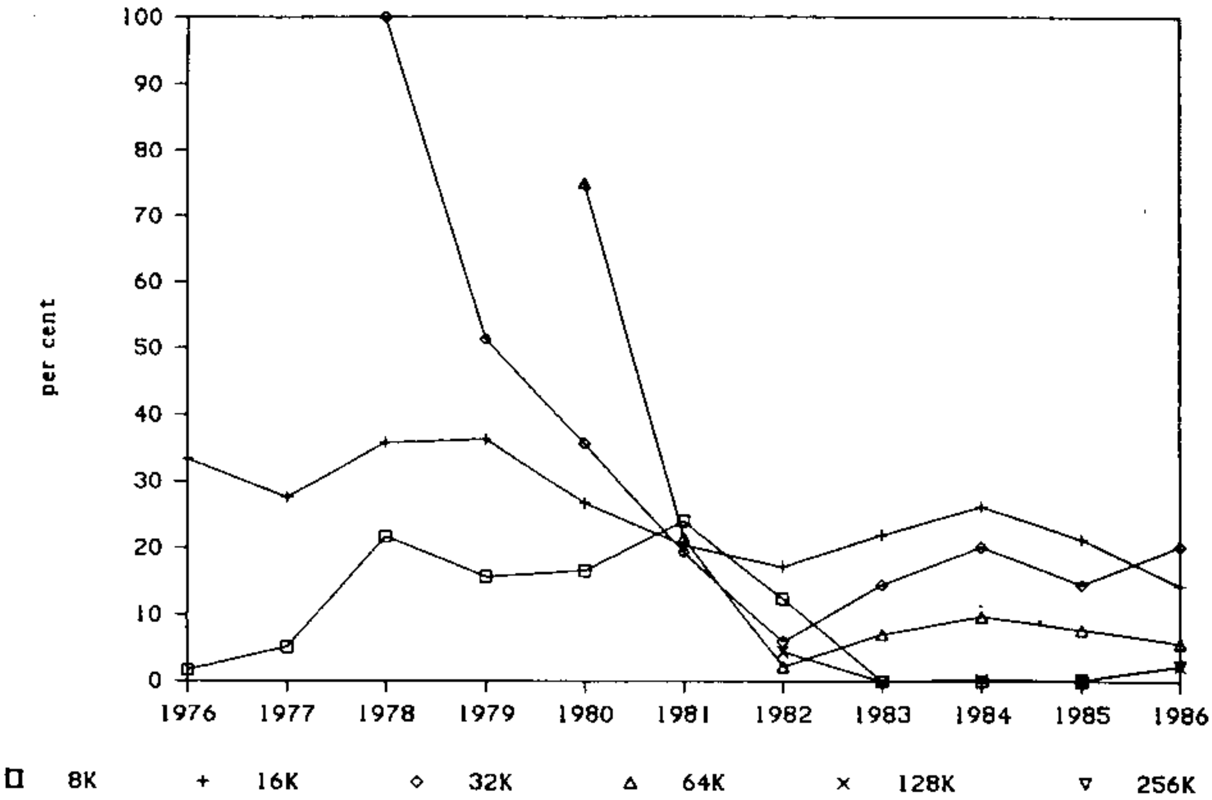


world-market shares for a given generation. As diagram 1 shows, this time profile of market shares is observed over all generations[3].

---

3 *"The firm has used a "cream-skimming" strategy rater than a forward pricing strategy used by a company such as Texas Instruments. Intel usually introduces a product early but at a high price and withdraws the product from the market after other firms begin marketing the product at lower prices."* Hazewindus and Tooker (1982) p.88.

Diagram 2. The market share pattern of the follower <u>Texas Instruments</u> for different generations of EPROMs.



The US producer Texas Instruments is known for its ability to produce high volumes efficiently and it enters when the market is large[4]. It can therefore be taken as an example for the follower

4 *"Texas Instruments is a highly efficient producer and is known for its marketing strategy of undercutting competitors' prices to capture a greater market share."* Hazewindus and Tooker (1982) p.86.

strategy. Though Texas Instruments' market share patterns are mixed one nevertheless may recognise a their tendency towards being relatively flat for each generation (Diagram 2).[5]

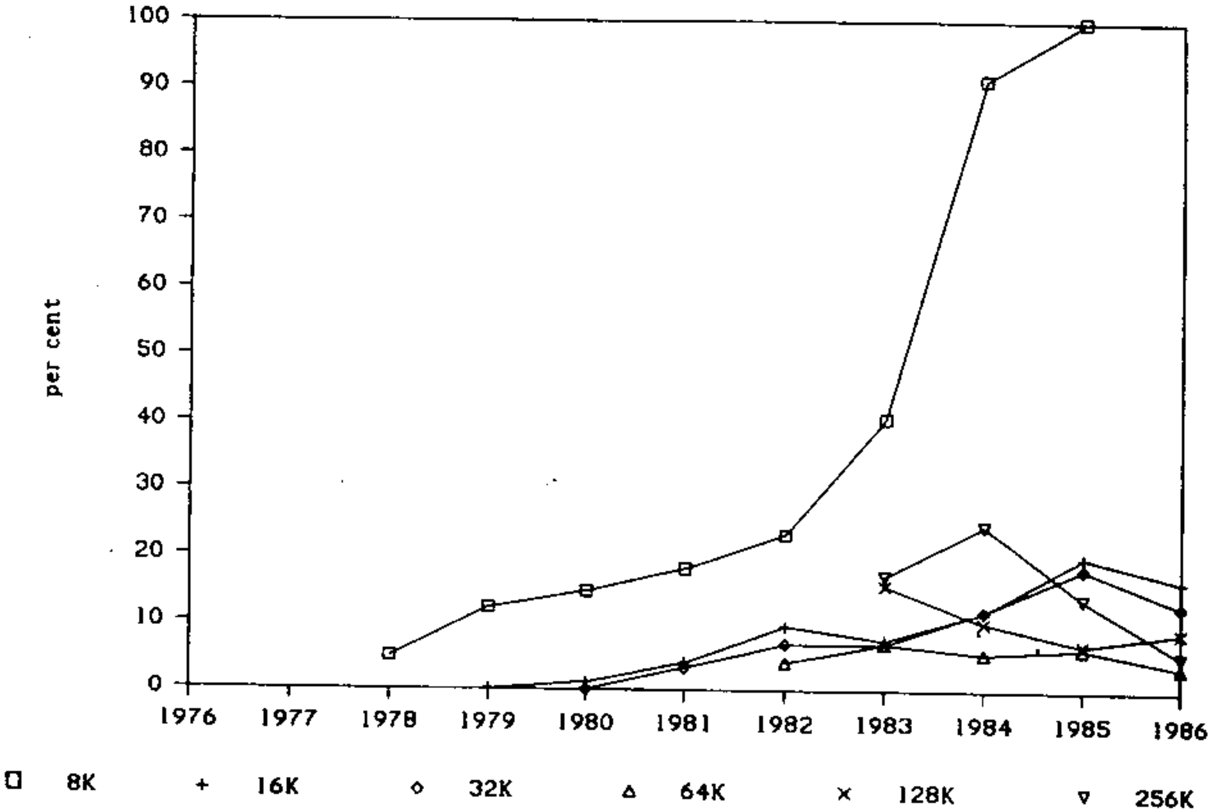
The US producer Advanced Micro Devices (AMD) has a time profile of market shares which is almost the opposite to that observed for the leader Intel. This firm, known as second source producer or imitator[6], enters late into a given generation and tries to stay until the end showing therefore increasing market shares over time (Diagram 3).

As a result one can clearly identify three strategy types pursued by different firms, and they seem to stick persistently to the same strategy. Intel, the innovative leader, adopts the creamskimming strategy which aims at being first in the market when prices are still high to recover the R&D outlays. The firm shifts to the next generation, and prices fall. The bulk of firms challenge the leading position of Intel. Though less inventive than Intel, they have a greater strength in volume production and

5 The 32k generation seems to be an exception. Texas Instruments enters first as a monopolist. However, one has to take into account that at the beginning of the generational cycle the market is very thin, and there are many firms that are able to produce prototypes of a new generation. In any case, there is a difference between prototype production and mass production for the latter requires a mastering of initial yield problems. Texas Instruments, when it moved in early was not able to maintain large market shares, whereas Intel, once it moved in, was also able to maintain large market shares for some years.

6 "*Its entry strategy was to second source integrated circuits, in both bipolar and MOS technologies, from other firms in the industry. AMD then improved on the performance, reliability, and the quality of these chips in this product line.*" Hazewindus and Tooker (1982) p.89.

Diagram 3. The market share pattern of the late entrant AMD for different generations of EPROMS.



marketing. Their entry causes prices to fall and the reduced margins are compensated by market expansion. Finally, there is one firm, AMD, which tries to exploit the market at the end of the cycle when prices are low but competitors are few.

Now the question arises whether these different strategies also involve different levels of profitability. Consider the EPROM market as a whole by aggregating over successive generations. By computing the market shares obtained by different firms in this newly-defined market one may also make deductions on profitability. Several empirical studies have shown a link between market shares and profitability[7]. Diagram A1 in Appendix IV shows the market shares for the overall EPROM market obtained by Intel, Texas Instruments, and AMD. Intel, through its *creamskimming* stategy has the largest market share in EPROMs all the time with the exception of 1979-80. Texas Instruments, through its strategy of undercutting prices when the market is large, has high market shares but they are generally well below Intel's with the already mentioned exception of 1979-80. AMD has the lowest overall market shares, except in 1985 and 1986 where it is overtaking Texas Instruments[8].

What has been shown seems to be a confirmation of the claim by Buzzell and Wiersema (1981 p.140) "*Whether connected with new product introduction or not, quality improvement is a powerful means of building market share...*" They show that the reactivity of market shares to quality improvements is particularly strong in industrial products.

Appendix IV presents other diagrams indicating features of the EPROM market. Diagram A2 shows that prices are high as the new generation is introduced and then falls steadily to virtually

7 For example see Buzzell et al. (1975,1981).

8 This might also be the effects of an attempted change in strategy by AMD. "*As the firm's sales grew, AMD changed its stategy to develop its own devices.*" Hazewindus and Tooker (1982) p.89.

the same level as the previous generations. As a result the per bit price of EPROMs falls from one generation to the next. The time profile of revenue from different memory devices shipped worldwide shows a hillshaped pattern where the peak tends to increase from generation to generation (Diagram A3).

Plotting the Herfindal index for each generation (Diagram A4), taking into account all firms in the market, one may observe a typically U-shaped time profile for all generations which reaches the minimum after about 5 years. This means that at the peak of the cycle the generation specific market is less concentrated than it is at the beginning and the end of the cycle.

3. REFERENCE TO EXISTING LITERATURE

Before proceding further it may be useful to define terms and relate to the literature on which the present work is based.

The explanation of observed industrial structure has proven to be a difficult task in the field of industrial organisation. A complex literature has grown in this context and it has given new insights. However, endemic multiplicity of equilibrium outcomes in oligopoly models, as a result of small changes in the basic assumptions, is one of the major obstacles to consensus. Nevertheless models of product differentiation may allow for sufficient flexibility in constructing a general model able to explain a large number of different industries (Shaked and Sutton, 1987). In this framework fixed cost, such as expenditures for R&D or advertising, may be used strategically by firms in order achieve dominance if these outlays lead to enhanced willingness to pay by customers.

Innovation refers either to the commercial introduction of a new product into the product range or to the adoption of a new technology. In the first case we have product innovation and in the latter case process innovation. Innovation involves a cost for the adopter. Problems of adoption have been studied extensively for process innovations. The cost of adoption is generally very high as the new process or product is invented since it takes considerable effort to make the invention marketable. Firms therefore are faced with the choice of either to wait for cost of adoption to decline or to adopt early in order to anticipate rivals. Reinganum (1981a) and Fudenberg and Tirole (1985) conducted a rigourous analysis of the duopoly game of adoption among identical firms with perfect information. Diffusion, i.e. sequential adoption, of an innovation occurs because it is assumed there is a positive net value of being first. However these authors only consider single innovations.

The models of Vickers (1986) and Beath *et al.* (1987) analyse a finite number of innovations which occur sequentially and discuss the question of who adopts the innovation: the pre-innovative leader or the pre-innovative follower. The innovation game takes the form of a bidding game for patents. There is no role in these models for the cost of innovation. The patent is bought by the firm who derives the greatest revenue increase from it. Since the innovating firm has an indeterminate monopoly over the innovation, the innovation can never diffuse in the conventional way through the industry, because it will never be adopted by more than one firm.

Thus one may distinguish two approaches. The first is based on the cost of adoption of a single innovation and it entails diffusion. The second is based on a sequence of innovations, without considering adoption costs, and in which the diffusion of the single innovation is virtually ruled out. The two approaches are integrated in the present paper, in which diffusion may occur over a sequence of innovations. The main emphasis is placed on the role of a particular learning assumption: adopting an innovation involves an externality. It allows the leader to achieve a knowledge advantage over non-adopters in the run-up for the subsequent innovation. The resulting outcome is striking. It ensures persistence of leadership in product innovation.

4. A MODEL OF VERTICAL PRODUCT DIFFERENTIATION

In this section the vertical product differentation model of Shaked and Sutton (1982) is taken and extended to the 3 firms case. The features of the model with 2 firms and under Cournot competition were analysed by Bonanno (1985). The present paper takes this extension a step further by introducing *learning by* *doing* in the sense defined above.

Assumptions on demand:

Assume a continuum of customers with identical tastes but different incomes[1] t. Income is distributed uniformly over the unit interval $t \in [0,1]$. Products are differentiated in quality denoted by the real number k where $k \in [a,b]$ with $b>a$. A higher k means higher quality and all customers agree on this if the product is supplied at cost. Customers make indivisible and mutually exclusive purchases and buy at most one unit. The utility function is

$$U(t,k)=u(k)\cdot(t-p_k) \tag{1}$$

where $u(k)$ denotes utility of consuming good of quality k with $u'(k)>0$, and p_k denotes the price of product with quality k. Define

$$t_k=-\frac{u(k-1)}{u(k)-u(k-1)}p_{k-1}+\frac{u(k)}{u(k)-u(k-1)}p_k \tag{2}$$

as the income level of the customer indifferent between quality k at price p_k and quality $k-1$ at price p_{k-1}, i.e it solves the equation $U(t_k,k)=U(t_k,k-1)$. Customers with income higher than t_k strictly prefer quality k, and customers with income lower than t_k strictly prefer quality $k-1$.

Assumptions on supply:

Assume that each firm supplies one quality only. The above partitioning of income space allows also for a partitioning of

1 Here income is to be understood as an indicator of the willingness to pay.

firms in the quality space. Firms have the opportunity to move away from each other in the product space. Firms offering a high quality product aim at rich customers, while firms offering an inferior quality aim at customers with lower income. Assuming zero costs firm *i* supplying quality *k* enjoys revenue

$$R_{ik} = p_k \cdot (t_{k+1} - t_k) \tag{3}$$

whereby *k+1* is the adjacent higher quality supplied by the competitor.

Given this set-up firms are playing the following three stage game. At stage 1 they decide upon entry, at stage 2 they choose quality, and at stage 3 they compete *à la* Cournot in quantities. Assume three firms. The following proposition holds:

> *Proposition 1:* If there are zero costs, the only Perfect Equilibrium of the three stage game involves all 3 firms entering and choosing highest feasible quality *b*. Each firm earns positive profits given by
>
> $$R = \frac{u(b) - u_0}{16u(b)} \tag{4}$$
>
> where u_0 is utility of not consuming the good and $0 < u_0 < u(a) < u(b)$.

For a proof of proposition 1 see Appendix 1.

The result of minimum differentiation in the case of firms competing *à la* Cournot in quantities depends crucially on the assumption of zero costs. Bonanno (1985) has shown that relaxing the assumption of zero costs one may actually get maximum differentiation in the case of 2 firms. I will extend similar considerations to the case of 3 firms.

For the sake of analytical tractability it is assumed that quality choices are discrete. Let firms choose among three different qualities u_1, u_2, and u_3 linked in the following way to each other: $u_3 = \gamma u_2 = \gamma^2 u_1$ with $\gamma > 1$. Furthermore assume also $u_1 = \gamma u_0$.

Quality is available at fixed cost $F(u_k) = \alpha u_k$ where $\alpha > 0$. The relationhip between fixed cost and quality is shown in Figure A1 in Appendix IV.

Define C_2 as the incremental fixed cost for quality increase from u_1 to u_2, and C_3 as the incremental fixed cost for quality increase from u_2 to u_3. So

(5) $$C_2 = F(u_2) - F(u_1) = \alpha u_2 - \alpha u_1 = \alpha(\gamma - 1)u_1$$

(6) $$C_3 = F(u_3) - F(u_2) = \alpha u_3 - \alpha u_2 = \gamma\alpha(\gamma - 1)u_1$$

Thus $C_3 = \gamma C_2$.

Assume $F(u_1)$ low enough to enable each firm to produce at least quality u_1 and to make positive profits. According to the levels of C_2 and C_3 firms now are given opportunity to differentiate.

Proposition 2: With fixed costs to improve quality, the Perfect Equilibrium of the three stage game may involve any outcome between minimum and maximum differentiation. If firms differentiate at equilibrium, then they enjoy different levels of profits. Profits are increase with quality.

In Appendix II an example is constructed where maximum differentiation occurs.

5. THE DIFFUSION OF NEW PRODUCTS

A dynamic form of the vertical product differentiation model with discrete quality choices is employed to analyse the diffusion of new quality products. There are three firms and three discrete levels of quality. We have a repetition of the game where firms once entered choose first quality and then quantities. This game is repeated an infinite number of times. Hence we have a infinite horizon supergame[10] which is made of the repetition of the following subgame:

CHOOSE QUALITY ------>CHOOSE QUANTITY

This can be thought of as firms facing a sequence of identical markets with time intervals depending on the repurchase time of the product.

Since there are 3 firms and 2 innovations, 6 different innovation times $\tau(i,k)$ are obtained. Without any loss of generality assume that firm 3 is the first to introduce u_2 and firm 2 is the

10 In an infinite horizon supergame firms could support the collusive outcome in each period according to the "Folk Theorem". In the sequel this is ruled out by assumption, as is generally done in the innovation literature.

second to introduce u_2 . 15 different innovation sequences are possible, denoted by Ω_j where j=1,...,15. They are shown on next page.

Make the following definitions:

Time denoted by T is continuous and running from 0 to ∞ .

$\tau(i,k)$: time at which firm i introduces quality u_k .

$\sigma(i,k)$: time at which any firm other than firm i changes any quality of its product before firm i introduces quality u_k .

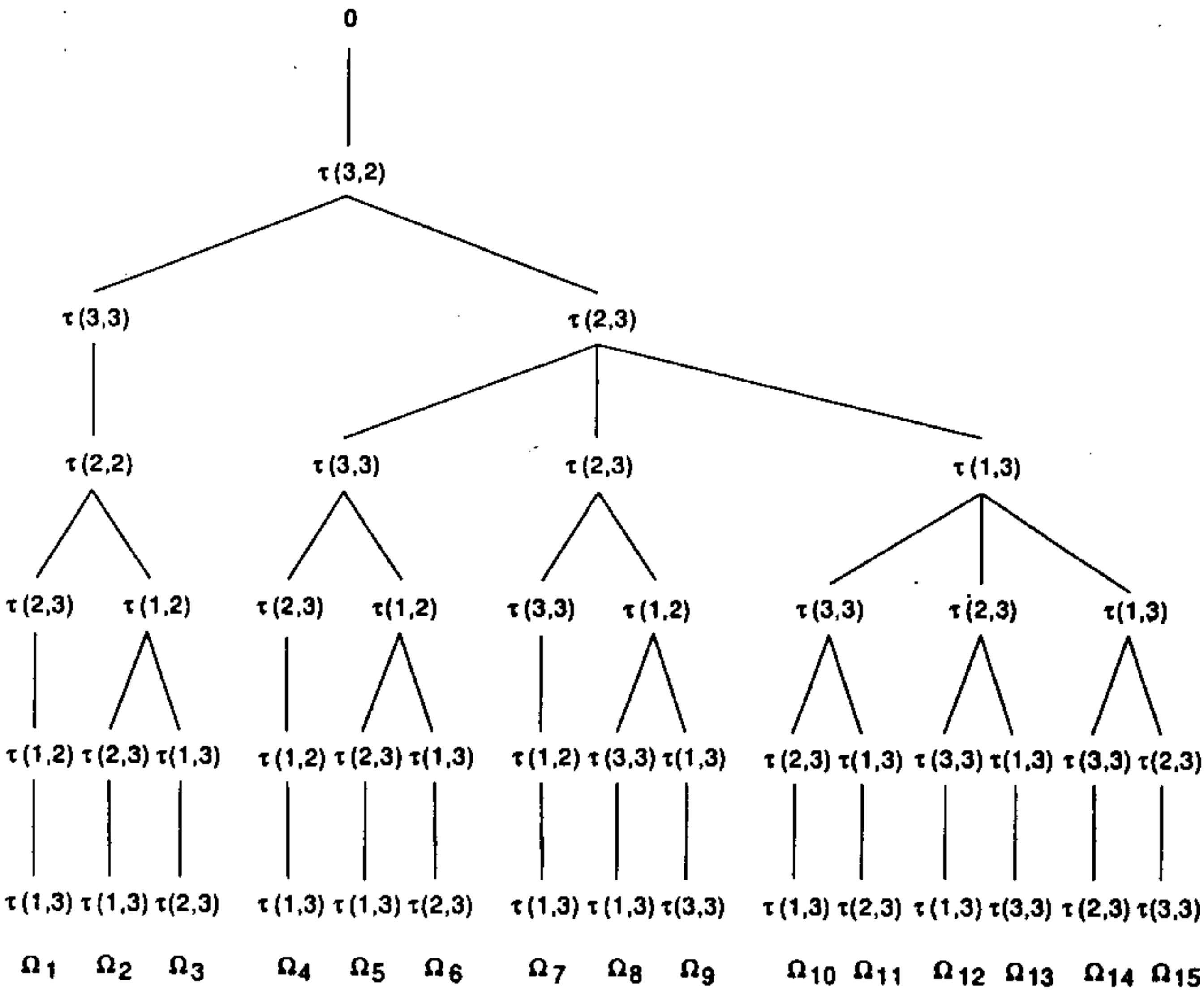
$\omega(i,k)$: time at which any firm other than firm i changes any quality of its product after firm i introduces quality u_k .

Hence if firm i is the first to introduce u_2 then $\sigma(i,2)=0$, and if it is the last to introduce u_3 , then $\omega(i,3)=\infty$.

Let $R_{ik}(\Omega_j)$ be the revenue of firm i producing quality k, given the quality choices of all other firms summarised by the parameter Ω_j .

Define $\Delta(i,k|\Omega_j)$ as the revenue increase to firm i due to introducing quality u_k , given the innovation sequence Ω_j .

Possible innovation patterns



The problem of the firm is one of timing of product innovations, i.e. of deciding upon when to introduce the new quality, given the decisions of other firms. Thus firm *i* maximizes the following profit function:

$$(7) \quad \max_{\tau(i,2),\tau(i,3)} V_i = \int_{\alpha(i,2)}^{\tau(i,2)} R_{i1}(\Omega_j)e^{-rT}dT + \int_{\tau(i,2)}^{\omega(i,2)} R_{i2}(\Omega_j)e^{-rT}dT + \int_{\alpha(i,3)}^{\tau(i,3)} R_{i2}(\Omega_j)e^{-rT}dT +$$

$$\int_{\tau(i,2)}^{\omega(i,3)} R_{i3}(\Omega_j)e^{-rT}dT + \hat{R}_i - \bar{C}_2[\tau(i,2)] - \bar{C}_3[\tau(i,3)]$$

for i=1,2,3.

whence r is the common interest rate, $\bar{C}_k[\tau(i,k)]$ the cost of bringing in innovation k=2,3 at time $\tau(i,k)$, and $\hat{R}_i$ is a sum of discounted revenue for firm i not affected by $\tau(i,2)$ and $\tau(i,3)$.

<u>Assumptions on cost:</u>

Let δ be the rate at which adoption cost falls over time.

Assumption 1.

$$C_k > \frac{R_{ik}(\Omega_j) - R_{ik-1}(\Omega_j)}{\delta + r}$$

for k=2,3, i=1,2,3, and j=1,2,...,15.

Assumption 2.

$$C_2[\tau(i,2)] = \exp\{-(r+\delta)\tau(i,2)\} \cdot C_2$$

Assumption 3.

$$C_3[\tau(i,3)] = \exp\{-r\tau(i,3) - \delta[\tau(i,3) - \tau(i,2)]\} \cdot C_3$$

Assumption 1 states that incremental costs C_2 and C_3 are initially so high that all firms produce quality u_1 . However incremental costs decline over time in the following way. C_2 starts to decline at rate δ from the beginning of the game (Assumption 2). From Assumption 3 derives that C_3 starts to decline at rate δ for a specific firm as soon as it starts to produce quality u_2. This assumption captures a sort of learning effect. Producing a given quality involves an externality. It induces a fall in the incremental cost of producing the subsequent quality[1]. It will turn out to be crucial in determining a certain innovation pattern.

The first order conditions for profit maximization for firm i are[2]

$$(8)\quad \Delta(i,2|\Omega_j) = R_{i2}(\Omega_j) - R_{i1}(\Omega_j) = (\delta + r)C_2 \cdot \exp\{-\delta\tau(i,2)\} - \delta C_3 \cdot \{-(\delta + r)[\tau(i,3) - \tau(i,2)]\}$$

$$(9)\quad \Delta(i,3|\Omega_j) = R_{i3}(\Omega_j) - R_{i2}(\Omega_j) = (\delta + r)C_3 \cdot \exp\{-\delta[\tau(i,3) - \tau(i,2)]\}$$

---

1 This is a well-known feature in some industries such as that for semiconductors. The initial yield in the production of a given memory chip generation is generally lower for a new entrant than for an experienced producer. Semiconductor production therefore entails a considerable "waste" of silicon, in particular in the early stage of the product life cycle when experience is little. One cost ot adopting a new generation of products may be identified with the total wastage over the relatively short 15-18 month period from the date of entry. Because this time span is so short the wastage can be modelled as a fixed cost.

2 These yield the open loop solutions which may well be subject to the criticism of not considering strategic interaction entirely. Unless information lags are very long preemption could occur (Fudenberg and Tirole (1985). However the high dimensional strategy space given by the 6 innovation times makes the computation of closed loop solutions extremely difficult.

Solving this simultaneous equation system gives the innovation times for each innovation sequence Ω_j where j=1...15.

$$(10)\quad \tau(i,2)=\frac{1}{\delta}\ln[(\delta+r)C_2]-\frac{1}{\delta}\ln\left[\Delta(i,2\mid\Omega_j)+\delta C_3\exp\left\{\frac{(\delta+r)}{\delta}\ln\left[\frac{\Delta(i,3\mid\Omega_j)}{(\delta+r)C_3}\right]\right\}\right]$$

$$(11)\quad \tau(i,3)=\tau(i,2)+\frac{1}{\delta}\{\ln[(\delta+r)C_3]-\ln[\Delta(i,3\mid\Omega_j)]\}$$

These first-order conditions refer to the single firm i only. In the attempt to solve the system of equations one has to take account of the fact that the revenue functions $R_{it}(\Omega_j)$ depend also on the innovation sequence. Therefore it is necessary to check if the innnovation times are consistent with the firms' positions in the quality space. This is done by the following procedure.

Step 1: Start from the origin of the game tree computing $\tau(3,2)$.

Step 2: Consider the subgames starting thereafter and compute the innovation times of their origins. The subgame with the earliest innovation time is then pursued.

Step 3: Repeat step 2 until a final node has been reached.

The first order conditions are highly non-linear in the model parameters γ , C_2 , δ , and r. Therefore numerical simulations had to be relied upon. It turns out that at a precommitment equilibrium the consistent innovation path is Ω_{10} , which implies the following order of innovations:

$$(12)\qquad \tau(3,2)<\tau(2,2)<\tau(1,2)<\tau(3,3)<\tau(2,3)<\tau(1,3)$$

This means none of the firms will innovate simultaneously, i.e. we have diffusion.[3] Furthermore the innovation sequence for quality u_2 is preserved also for quality u_3. The typical time profile of innovation is represented in Figure A2 in Appendix IV.

Firm 3, which is the leader in introducing quality u_2, is also leader in the introduction of quality u_3. The followers enter in the same order into the market for quality u_3 as they did for quality u_2 (i.e. first firm 2 then firm 1).

Rewriting equations (10) and (11) under the assumption[4] of $r=0$ gives a more straightforward intuituion of the strong result of complete diffusion quality u_2 before quality u_3 is introduced.

$$(13)\quad \tau(i,2)=\frac{1}{\delta}\ln\left\{\frac{\delta C_2}{\Delta(i,2|\Omega_j)+\Delta(i,3|\Omega_j)}\right\}$$

$$(14)\quad \tau(i,3)=\frac{1}{\delta}\ln\left\{\frac{\delta^2\cdot C_2\cdot C_3}{\Delta(i,3|\Omega_j)\cdot[\Delta(i,2|\Omega_j)+\Delta(i,3|\Omega_j)]}\right\}$$

If firm 1 is the last to adopt quality u_2 and if firm 3 the leader in adopting quality u_2, then firm 3 is also the first to adopt quality u_3. Firm 1 in any case introduces u_2 before firm 3 adopts quality u_3 because the following condition is always satisfied[5]

$$(15)\qquad \Delta(1,2)+\Delta(1,3)>\frac{\Delta(3,3)\cdot[\Delta(3,2)+\Delta(3,3)]}{\delta C_3}$$

3 This result is isomorphic to the diffusion result as open loop equilibrium obtained by Reinganum (1981a, 1981b). However she considers process innovations which occur only once.

4 With $r=0$ firms place most value on future profits. If the persistence of leadership result holds under $r=0$, then it holds also under $r>0$.

5 This is derived from $\tau(1,2)<\tau(3,3)$

The numerator of the right-hand side represents an increasing function of the marginal revenues to the leader. These rise as quality increases. However this is more than offset by the augmented incremental cost C_3 which rises also with quality.

Thus no firm will be *leapfrogged* at any time even though *leapfrogging* is a general result with Cournot competion (Vickers 1986). Here *persistence of leadership* is the result because of the first mover advantage derived from learning.[6] Notice that this result implies also that firm 3 has a higher present discounted value of profits than firm 2, and firm 2 has a higher present discounted value of profits than firm 1.[7]

---

6 This result is general, holding for any reasonable parameter values in the simulation exercise. Furthermore it is also robust against changes in the cost function, as for example exponential cost functions of the type $F(u_k)=\exp(\alpha u_k)$.

7 Profit differences may induce preemption in order to equalize rents unless information lags are infinite. On problems with open loop equilibria in this context see Fudenberg and Tirole (1985).

Table 1. The possible outcomes by removing Assumption 3.

$0 < \gamma \leq 1.25$	Increasing dominance by firm 3. It adopts u_3 before neither firm 2 nor firm 1 have adopted u_2 .
$1.25 < \gamma \leq 1.65$	Leapfrogging by firm 2. It adopts u_3 after firm 3 has adopted u_2 .
$1.65 < \gamma \leq 4.25$	Leapfrogging by firm 1. It adopts u_3 after both firm 3 and firm 2 have adopted u_2 .
$4.25 < \gamma$	Diffusion. Firms adopt sequentially first u_2 , and then u_3 . Any firm may be the first adopter of u_3 .

Remark: Assumption 3 is crucial for generating this result. Suppose Assumption 3 is replaced by an assumption identical to Assumption 2, in other words incremental costs C_3 too fall from the beginning of the game at rate δ . This implies that there is complete spillover of learning in production of u_3 . The possible outcomes depend on the values of γ , the degree of quality increase. Table 1 shows the summary results. One should note that for small quality innovations the outcome is increased dominance, for intermediate degrees of innovation one gets some sorts of leap-frogging, and for relatively large values diffusion. The case for small and intermediate values of quality innovations may be related to the findings of the patent race for product innovation. For example Beath *et al.* (1987) show that with Bertrand competition for small product innovations increasing dominance occurs, whereas for larger innovations action-reaction is the outcome. The diffusion outcome here, not possible in the Beath *et al.* model because firms compete in prices, is driven by the fact that as quality increases adoption cost increases as well. Thus a critical point is reached where all firms prefer to wait and produce the same quality before they start to adopt a new quality. This diffusion outcome however does not imply anything about who is the leader in the adoption of u_3 . It could be any of the three firms.

From this one can conclude that Assumption 3 is a *sufficient* condition for generating the joint outcome of diffusion and persistence of leadership.

In the following a series of implications for basic variables such as market shares, price, industry revenue, and concentration index are derived with all the above assumptions on cost applying. The corresponding algebric expressions may be found in Appendix II. Figure 1 shows the evolution of market shares for the leader (firm 3), which always enters first into a new product market. He takes advantage of the initially high prices to recover fixed costs. Due to subsequent entry his market share declines steadily for a given product and eventually becomes zero as he moves up to the higher quality. This strategy has also been referred to as "creamskimming".[8] Figure 2 depicts the evolution of market shares of firm 2. With the entry of firm 2, the challenger, the growth phase of the cycle begins. His market share pattern has a U-shaped time profile. Figure 3 shows the time profile of market shares for firm 1, the late entrant, which enters as the product is reaching maturity. Whereas other firms are moving out, this firm stays until to the end of the life cycle. Thus it has increasing market shares over time for a given product.

The time profile of prices is represented in figure A3 in Appendix IV. Prices are high when the new quality is introduced and then they decline. The time profile of industry revenue $\bar{R}_t$

8 Kotler (1984) ch.11.

Figure 1. The market share pattern of firm 3, the innovative leader, for different products.

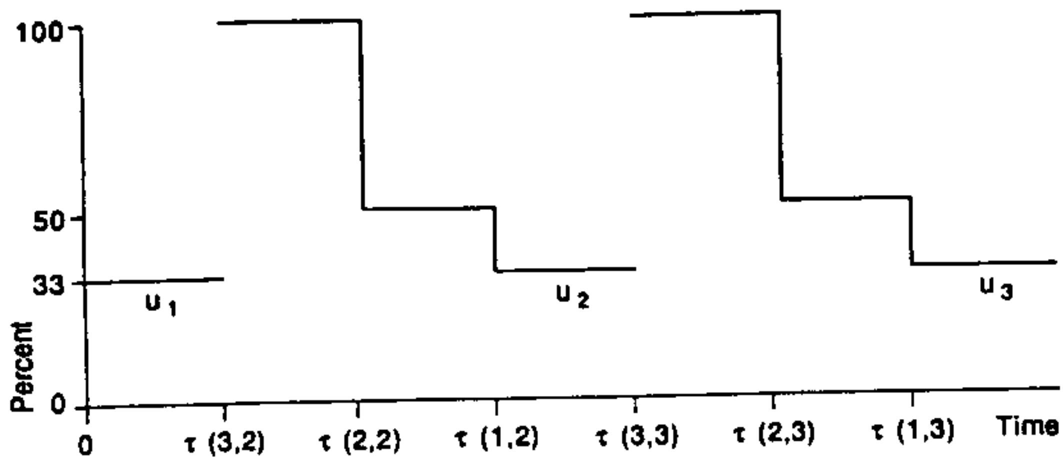


Figure 2. The market share pattern of firm 2, the follower, for different products.

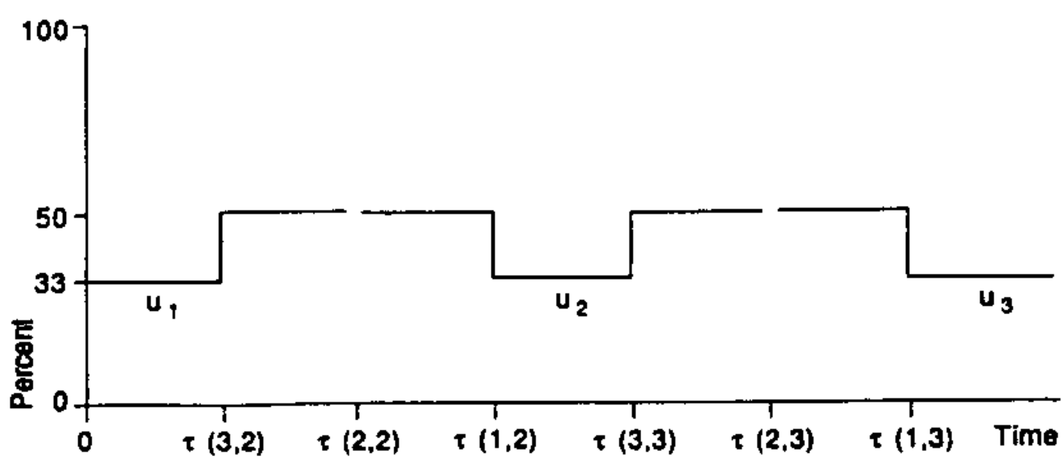
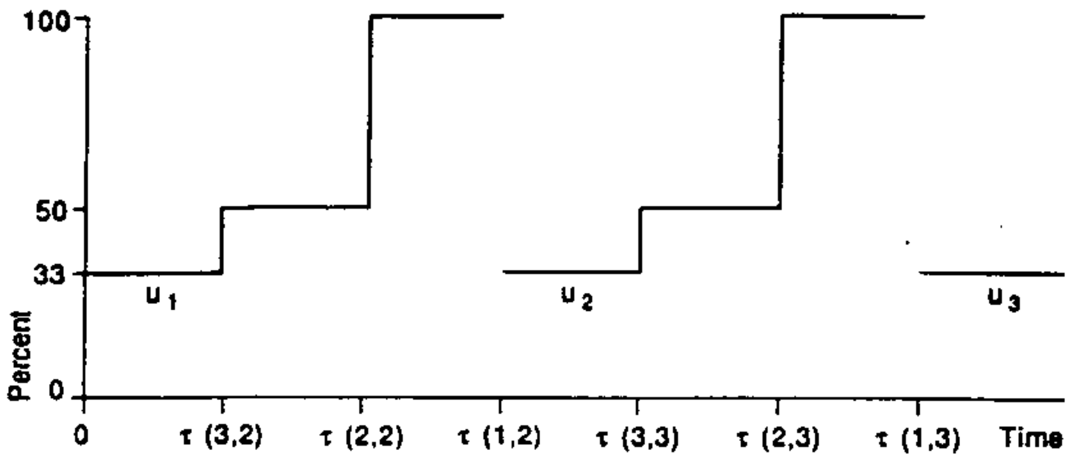


Figure 3. The market share pattern of firm 1, the late entrant, for different products.



from quality u_k for k=1,2,3 is hillshaped[9] as shown in figure A4 in Appendix IV. One can see that the industry revenue reaches peaks which become higher as quality increases. Finally, as a result of firms adopting the strategies set out above, we have a market which is monopolized at the beginning and at the end of the product cycle, but shows lower concentration in the middle of the product cycle. Hence the Herfindal index H for the market defined by different qualities has a U-shaped form as shown in figure A5 in Appendix IV.

9 It is well known from the business literature that sales of new product follow typically a hillshaped pattern. An unsettled question is whether the product life cycle is a result of firms' strategies or rather a natural evolution of demand (Kotler 1984, ch.11). In this paper demand is actually neutral in this respect and the product life cycle is the result of firms trying to improve quality attributes under the constraint of fixed costs.

6. CONCLUSIONS

This model is an attempt to generate endogenously asymmetries in firms' strategies which imply also differences in profitability. The model generates waves of new quality products coming in sequentially with falling prices. Different strategies are reflected in different dynamics of market shares. A particular form of learning by doing turns out to be the basic assumption for the *persistence of leadership* result combined with diffusion of new products. The implications of the model seem to fit remarkably well to stylized facts observed in the market for EPROM chips, a product taken from the semiconductor industry where learning by doing knowingly plays a large role. Because the production of memory chips is a batch process and the production yield follows the learning curve, a lot of silicon must be discarded during the early stages of a new generation. Since the time horizon for a generation is low, this can be regarded as the fixed cost for supplying a higher density generation. This also makes *leapfrogging* extremely costly. As a result one obtains stability of market share patterns over generations for some firms, such as the leading innovator Intel, which achieves a high overall market share through continuous product innovation.

Recent events in the semiconductor market suggest that some new patterns are emerging. In the market for Dynamic Random Access Memories (DRAMs) the inventor Intel has been *leapfrogged* in product innovation. The reasons for this turn of events will be subject of a second paper.

APPENDIX I

Proof of Proposition 1: This is an extension of the minimum differentiation result shown by Bonanno (1985,p.100) for the 2 firms case. Let k_i be the quality choosen by firm i=1,2,3, whereby $k_3 \geq k_2 \geq k_1$. Let $x = u(k_1), y = u(k_2), z = u(k_3)$. Hence $z \geq y \geq x$. q_i is the demand for firm i, which is given by the consumers in the following income segments:

$$q_1 = t_{k2} - t_{k1} \qquad q_2 = t_{k3} - t_{k2} \qquad q_3 = 1 - t_{k3}$$

For a given triple (x,y,z) we can derive the inverse demand functions

$$p_1 = G_1(q_1, q_2, q_3, x, y, z) = -\frac{x-u_0}{x}q_1 - \frac{x-u_0}{x}q_2 - \frac{x-u_0}{x}q_3 + \frac{x-u_0}{x}$$

$$p_2 = G_2(q_1, q_2, q_3, x, y, z) = -\frac{x-u_0}{y}q_1 - \frac{y-u_0}{y}q_2 - \frac{y-u_0}{y}q_3 + \frac{y-u_0}{y}$$

$$p_3 = G_3(q_1, q_2, q_3, x, y, z) = -\frac{x-u_0}{z}q_1 - \frac{y-u_0}{z}q_2 - \frac{z-u_0}{z}q_3 + \frac{z-u_0}{z}$$

The revenue function is given by

$$R_i(q_1, q_2, q_3, x, y, z) = q_i G_i(q_1, q_2, q_3, x, y, z) \qquad \text{for } i = 1,2,3.$$

Firms are assumed to compete *à la* Cournot at stage 3 of the game. Solving the system

$$\frac{\partial R_i}{\partial q_i} = 0 \qquad \text{for } i = 1,2,3$$

This gives the following revenue functions at stage 2

$$\hat{R}_1(x,y,z)=\frac{(z-u_0)^2(y-u_0)^2(x-u_0)}{4x[(z-u_0)(4y-x-3u_0)-(y-u_0)^2]^2}$$

$$\hat{R}_2(x,y,z)=\frac{(z-u_0)^2(2y-x-u_0)^2(y-u_0)}{4y[(z-u_0)(4y-x-3u_0)-(y-u_0)^2]^2}$$

$$\hat{R}_3(x,y,z)=\frac{(z-u_0)^2[(z-u_0)(4y-x-3u_0)-2(y-u_0)^2]^2}{4z[(z-u_0)(4y-x-3u_0)-(y-u_0)^2]^2}$$

Let W=$U([a,b])$ and $Q=\{(x,y,z)\in W^3/z\geq y\geq x\}$. The following holds:

$$\frac{\partial\hat{R}_1}{\partial k_1}=\frac{\partial\hat{R}_1}{\partial x}U' \qquad \frac{\partial\hat{R}_2}{\partial k_2}=\frac{\partial\hat{R}_2}{\partial y}U' \qquad \frac{\partial\hat{R}_3}{\partial k_3}=\frac{\partial\hat{R}_3}{\partial z}U'$$

To show that

$$\frac{\partial\hat{R}_i}{\partial k_i}>0 \qquad \text{for } i=1,2,3$$

it is sufficient to prove that $\frac{\partial\hat{R}_1}{\partial x}$, $\frac{\partial\hat{R}_2}{\partial y}$, and $\frac{\partial\hat{R}_3}{\partial z}$ are positive on Q. Since U' is positive by assumption one has to show that the following expressions are positive

$$\frac{\partial\hat{R}_1}{\partial x}=\hat{R}_1\cdot\left[\frac{u_0}{x(x-u_0)}+\frac{2(z-u_0)}{(z-u_0)(4y-x-3u_0)-(y-u_0)^2}\right]$$

$$\frac{\partial\hat{R}_2}{\partial y}=\hat{R}_2\cdot\left[\frac{u_0}{y(y-u_0)}+\frac{4(x-u_0)(z-y)+4(y-u_0)^2}{(2y-x-u_0)[(z-u_0)(4y-x-3u_0)-(y-u_0)^2]}\right]$$

$$\frac{\partial\hat{R}_3}{\partial z}=\hat{R}_3\cdot\left[\frac{u_0}{z(z-u_0)}+\frac{2(4y-x-u_0)(y-u_0)^2}{[(z-u_0)(4y-x-3u_0)-(y-u_0)^2][(z-u_0)(4y-x-3u_0)-2(y-u_0)^2]}\right]$$

Given that on Q we have $z\geq y\geq x$ all three derivatives are positive. Thus the three stage game has a unique Perfect Equilibrium where $k_1=k_2=k_3=b$. Substituting into the revenue function gives

$$\hat{R}_1 = \hat{R}_2 = \hat{R}_3 = \frac{u(b)-u_0}{16u(b)}$$

QED.

APPENDIX II

Proof of Proposition 2: This is an example where maximum differentiation may occur even if firms compete *à la Cournot* in quantities at stage 3 of the game. Let $Z=(u_1,u_2,u_3)$ and let $Q=\{(x,y,z)\in Z^3/z\geq y\geq x\}$.

At stage 2 of the 3 stage game firms maximize the following profit functions:

$$\text{Firm 1:} \quad \max_x \Pi_1(x,y,z)=\hat{R}_1(x,y,z,)-F(x)$$

$$\text{Firm 2:} \quad \max_y \Pi_2(x,y,z)=\hat{R}_2(x,y,z,)-F(y)$$

$$\text{Firm 3:} \quad \max_z \Pi_3(x,y,z)=\hat{R}_3(x,y,z,)-F(z)$$

Consider the following conditions:

C1. $$C_2+C_3<\frac{(u_3-u_0)[(u_3-u_0)(4u_2-u_1-3u_0)-2(u_2-u_0)^2]^2}{4u_3[(u_3-u_0)(4u_2-u_1-3u_0)-(u_2-u_0)^2]^2}-\frac{(u_1-u_0)}{16u_1}$$

RHS of above inequality is the marginal revenue to the firm choosing u_3 when the other firms choose respectively u_1 and u_2 .

C2. $$C_2+C_3>\frac{(u_3-u_0)(2u_3-u_1-u_0)^2}{4u_3(3u_3-u_1-2u_0)^2}-\frac{(u_1-u_0)}{16u_1}$$

RHS of above inequality is the marginal revenue to the firm choosing u_3 when the other firms choose respectively u_1 and u_3.

C3. $$C_2 < \frac{(u_3-u_0)^2(2u_2-u_1-u_0)^2(u_2-u_0)}{4u_2[(u_3-u_0)(4u_2-u_1-3u_0)-(u_2-u_0)^2]^2}-\frac{(u_1-u_0)}{16u_1}$$

RHS of above inequality is the marginal revenue to the firm choosing u_2 when the other firms choose respectively u_1 and u_3.

C4. $$C_2 > \frac{(u_3-u_0)^2(u_2-u_0)}{4u_2(3u_3-u_2-2u_0)^2}-\frac{(u_1-u_0)}{16u_1}$$

RHS of above inequality is the marginal revenue to the firm choosing u_2 when the other firms choose respectively u_2 and u_3 .

If these conditions are satisfied, then the Perfect Equilibrium involves $x=u_1$, $y=u_2$, and $z=u_3$. This example of maximum differentiation is supported by the following parameter values $\gamma=2$, $C_2=0.15$.

By subtracting inequality C3 from inequality C4 one can show that at equilibrium $\Pi_3>\Pi_2$, and from inequality C3 emerges that $\Pi_2>\Pi_1$. Thus, differentiation leads to different levels of profitability, whereby firms supplying higher quality obtain higher profits.

APPENDIX III

The time profile of prices is as follows

$0 \le T < \tau(3,2)$: $p_1 = (\gamma - 1)/(4\gamma)$; u_2 and u_3 are not produced

$\tau(3,2) \le T < \tau(2,2)$:

$$p_1 = \frac{(\gamma-1)(\gamma^2-1)}{2\gamma(3\gamma^2-\gamma-2)} \qquad p_2 = \frac{(\gamma^2-1)(3\gamma^2-2\gamma-1)}{2\gamma^2(3\gamma^2-\gamma-2)};$$ u_3 is not produced

$\tau(2,2) \le T < \tau(1,2)$:

$$p_1 = \frac{(\gamma-1)(\gamma^2-1)}{2\gamma(3\gamma^2-\gamma-2)} \qquad p_2 = \frac{(\gamma^2-1)(2\gamma^2-\gamma-1)}{2\gamma^2(3\gamma^2-\gamma-2)};$$ u_3 is not produced

$\tau(1,2) \le T < \tau(3,3)$: $p_2 = \frac{(\gamma^2-1)}{4\gamma^2}$; u_1 and u_3 are not produced

$\tau(3,3) \le T < \tau(2,3)$:

$$p_2 = \frac{(\gamma^2-1)(\gamma^3-1)}{2\gamma^2(3\gamma^3-\gamma^2-2)} \qquad p_3 = \frac{(\gamma^3-1)(3\gamma^3-2\gamma^2-1)}{2\gamma^3(3\gamma^3-\gamma^2-2)};$$ u_1 is not produced

$\tau(2,3) \le T < \tau(1,3)$:

$$p_2 = \frac{(\gamma^2-1)(\gamma^3-1)}{2\gamma^2(3\gamma^3-\gamma^2-2)} \qquad p_3 = \frac{(\gamma^3-1)(2\gamma^3-\gamma^2-1)}{2\gamma^3(3\gamma^3-\gamma^2-2)};$$ u_1 is not produced

$\tau(1,3) \le T$: $p_3 = \frac{(\gamma^3-1)}{4\gamma^3}$; u_1 and u_2 are not produced

The time profile of industry revenue $\bar{R}_k$ from quality u_k for $k=1,2,3$ is:

$0 \le T < \tau(3,2)$: $\bar{R}_1 = 3(\gamma-1)/(16\gamma)$ $\bar{R}_2 = \bar{R}_3 = 0$

$\tau(3,2) \le T < \tau(2,2)$:

$$\bar{R}_1 = \frac{(\gamma-1)(\gamma^2-1)^2}{2\gamma(3\gamma^2-\gamma-2)^2} \qquad \bar{R}_2 = \frac{(\gamma^2-1)(3\gamma^2-2\gamma-1)^2}{4\gamma^2(3\gamma^2-\gamma-2)^2} \qquad \bar{R}_3 = 0$$

$\tau(2,2) \leq T < \tau(1,2)$:

$$\bar{R}_1 = \frac{(\gamma-1)(\gamma^2-1)^2}{4\gamma(3\gamma^2-\gamma-2)^2} \qquad \bar{R}_2 = \frac{(\gamma^2-1)(2\gamma^2-\gamma-1)^2}{2\gamma^2(3\gamma^2-\gamma-2)^2} \qquad \bar{R}_3 = 0$$

$\tau(1,2) \leq T < \tau(3,3)$:

$$\bar{R}_2 = \frac{3(\gamma^2-1)}{16\gamma^2} \qquad \bar{R}_1 = \bar{R}_3 = 0$$

$\tau(3,3) \leq T < \tau(2,3)$:

$$\bar{R}_2 = \frac{(\gamma^2-1)(\gamma^3-1)^2}{2\gamma^2(3\gamma^3-\gamma^2-2)^2} \qquad \bar{R}_3 = \frac{(\gamma^3-1)(3\gamma^3-2\gamma^2-1)^2}{4\gamma^3(3\gamma^3-\gamma^2-2)^2} \qquad \bar{R}_1 = 0$$

$\tau(2,3) \leq T < \tau(1,3)$:

$$\bar{R}_2 = \frac{(\gamma^2-1)(\gamma^3-1)^2}{4\gamma^2(3\gamma^3-\gamma^2-2)^2} \qquad \bar{R}_3 = \frac{(\gamma^3-1)(2\gamma^3-\gamma^2-1)^2}{2\gamma^3(3\gamma^3-\gamma^2-2)^2} \qquad \bar{R}_1 = 0$$

$\tau(1,3) \leq T$:

$$\bar{R}_3 = \frac{3(\gamma^3-1)}{16\gamma^3} \qquad \bar{R}_1 = \bar{R}_2 = 0$$

Diagram A1. Market shares of selected firms in the EPROM market by aggregating revenues from successive generations.

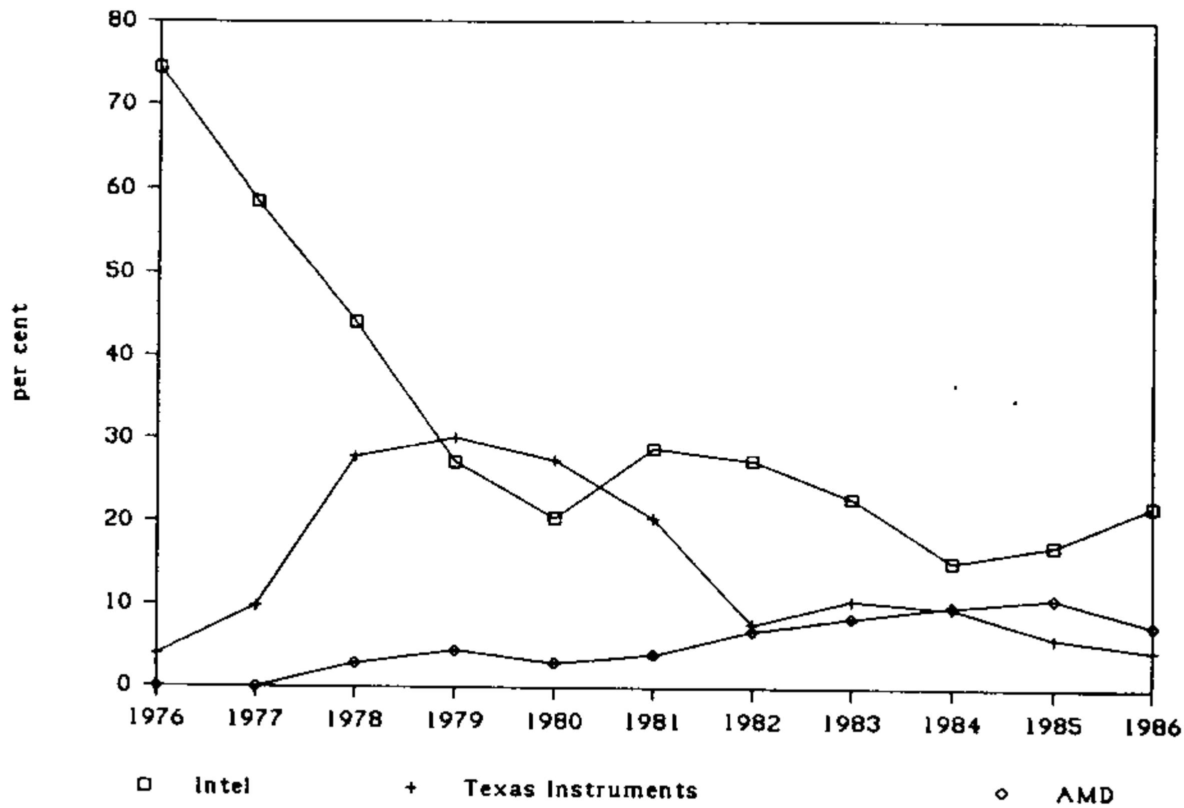


Diagram A2. Average selling prices

for different generations of EPROMs (US $)

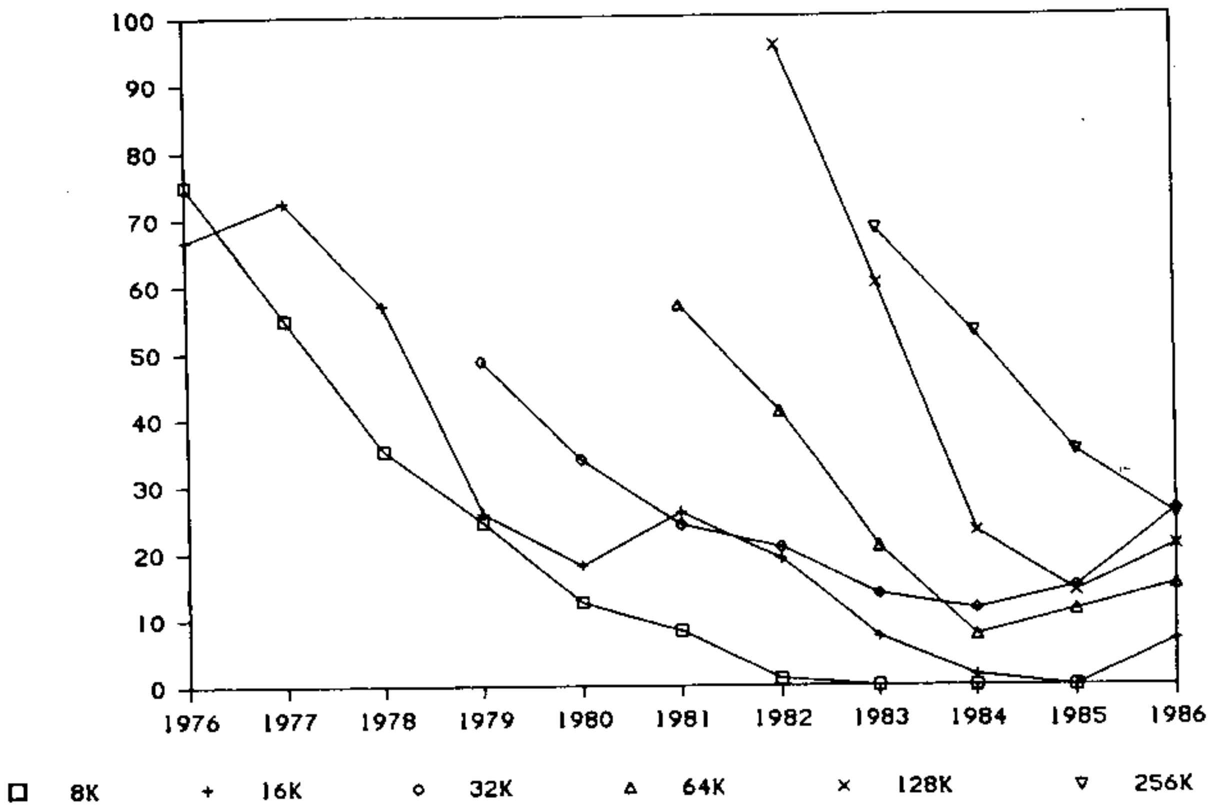


Diagram A3. Revenues from worldwide sales for different generations of EPROMs (US $ Millions)

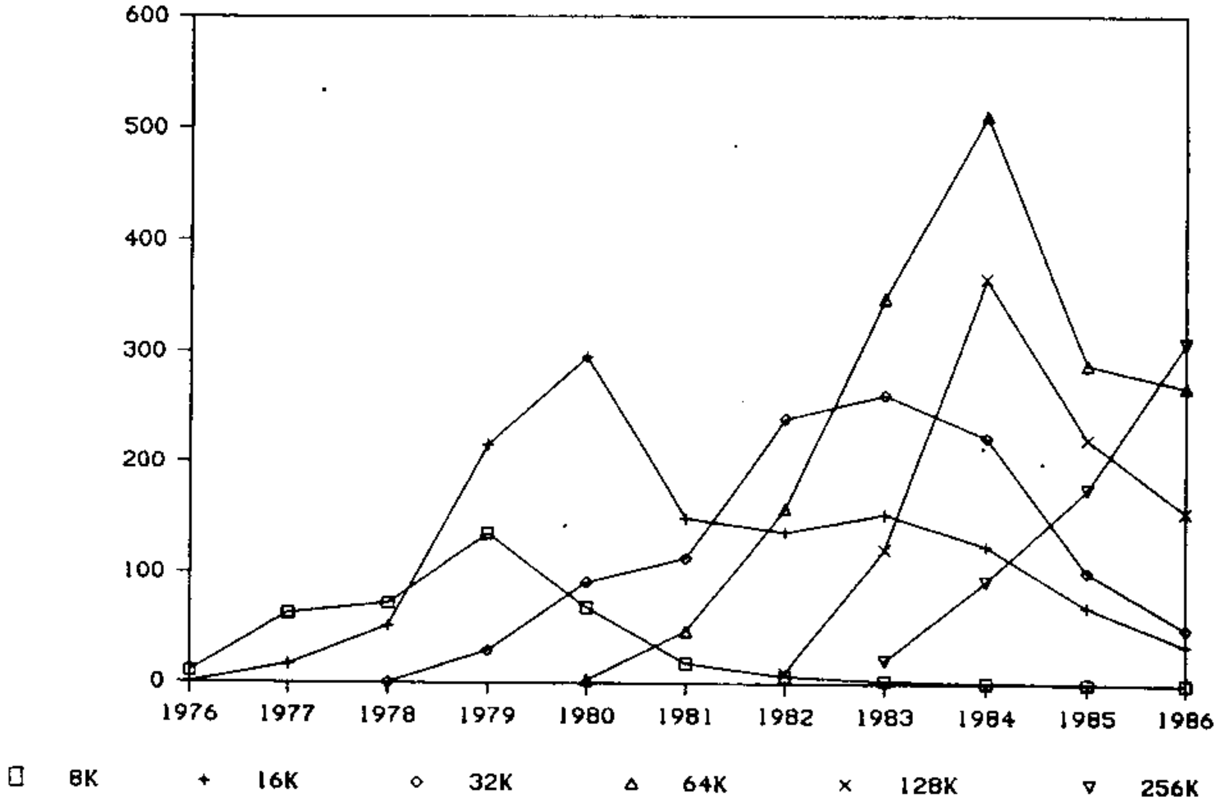


Diagram A4. Herfindal index

for different generations of EPROMs

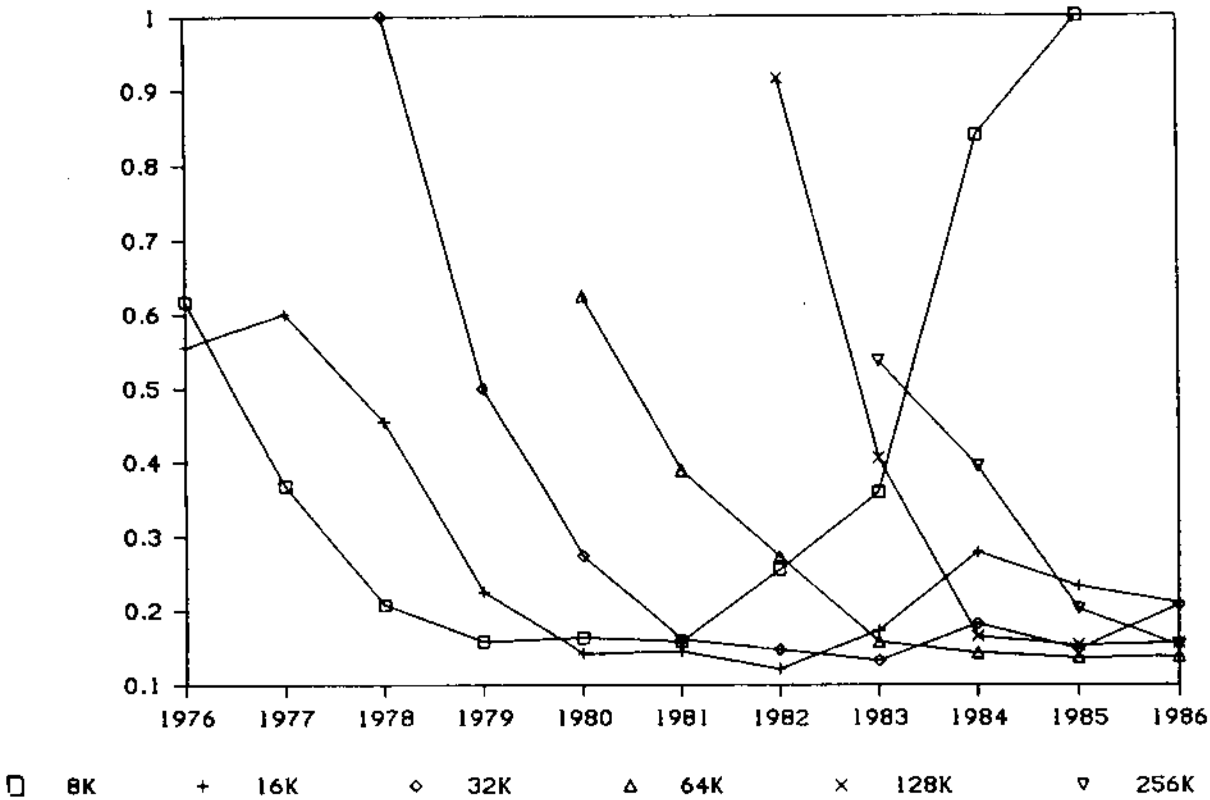


Figure A1. The fixed cost function.

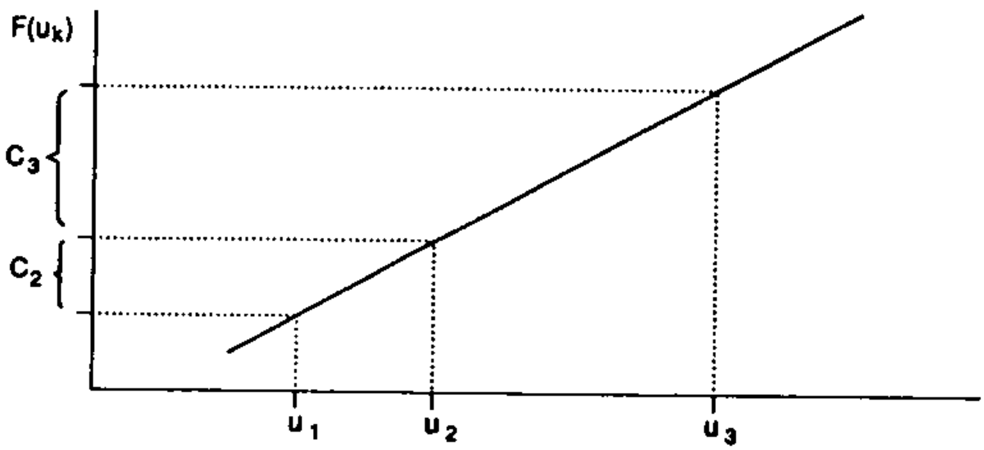


Figure A2. The innovation pattern for firms at equilibrium.

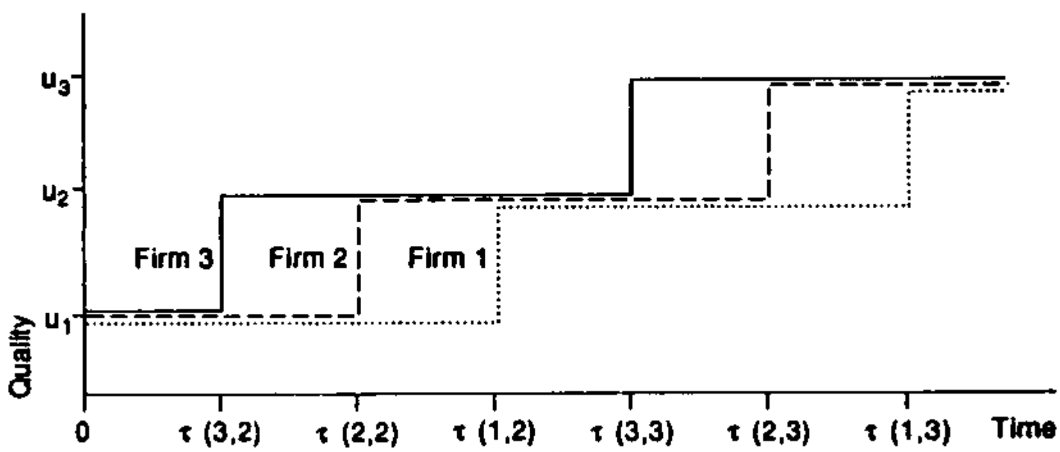


Figure A3. The time profile of prices for different qualities.

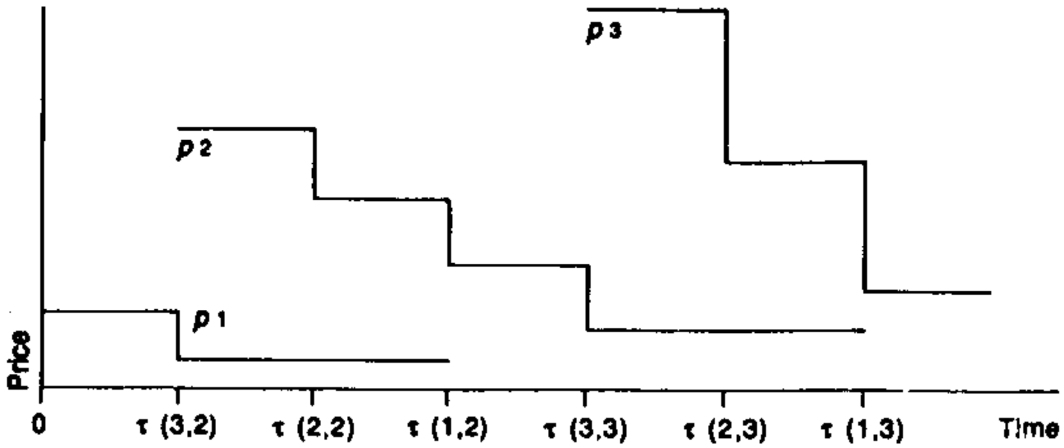


Figure A4. The time profile of industry revenues by product quality.

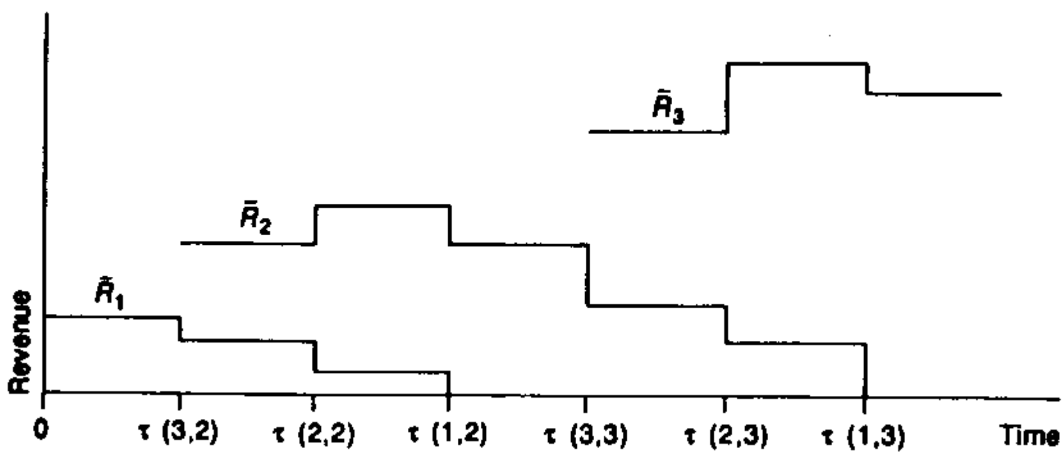
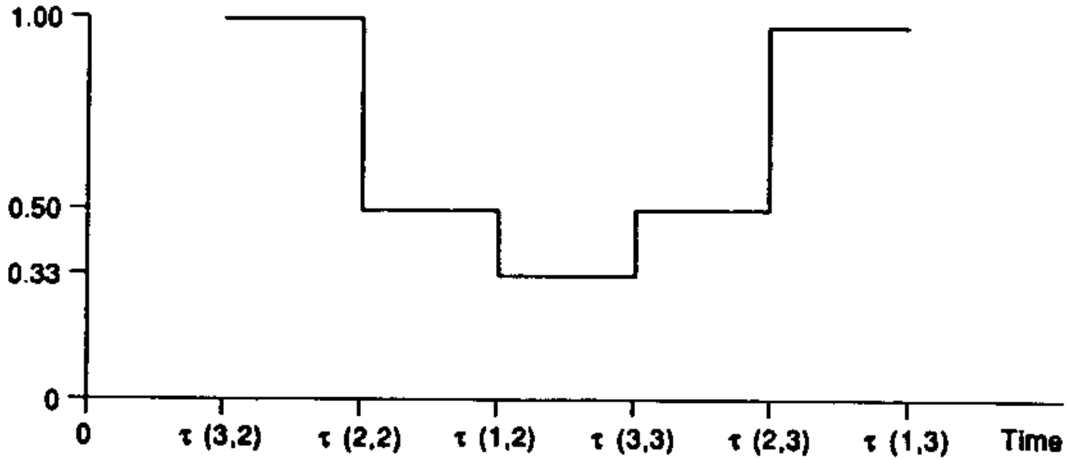


Figure A5. The Herfindal index for quality u_2.



BIBLIOGRAPHY

Beath, John, Yannis Katsoulacos and David Ulph "Sequential Product Innovation and Industry Evolution." *Economic Journal*, Vol. 97 Conference, 1987, 23-43.

Bonanno, Giacomo. "*Topics in Oligoply.*" unpublished Ph.D. thesis, London School of Economics, 1985.

Buzzell, Robert D., Bradley T. Gale, and Ralph F.M. Sultan "Market Share-A Key to Profitability." *Harvard Business Review*, Jan-Feb. 1975, 97-106.

Buzzell, Robert D. and Frederik D. Wiersema "Successful Share-Building Strategies. *Harvard Business Review*, Jan-Feb. 1981, 135-44.

Fudenberg, Drew and Jean Tirole. "Preemption and Rent Equalization in the Adoption of a New Technology." *Review of Economic Studies*, Vol.52, 1985, 383-401.

Hazewindus, Nico and John Tooker. "*The US Microelectronics Industry.*" Pergamon Press, New York, 1982.

Kotler, Philip. "*Marketing Management: Analysis, Planning, and Control.*" Englewood Cliffs, N.J., Prentice Hall, 5th ed. 1984.

Reinganum, Jennifer F. "On the Diffusion of New Technology: A Game Theoretic Approach." *Review of Economic Studies*, Vol.48, 1981a, 395-405.

Reinganum, Jennifer F. "Market Structure and the Diffusion of New Technology." *Bell Journal of Economics*, Vol.12, 1981b, 618-24.

Shaked, Avner and John Sutton. "Relaxing Price Competition Through Product Differentiation." *Review of Economic Studies*, Vol.49, 1982, 3-13.

Shaked, Avner and John Sutton. "Natural Oligopolies." *Econometrica*, Vol.51, 1983, 1469-83.

Shaked, Avner and John Sutton. "Product Differentiation and Industrial Structure." *The Journal of Industrial Economics*, Vol.36, 1987, 131-46.

Sutton, John. "Vertical Product Differentiation: Some Basic Themes." *American Economic Review. Papers & Proceedings*, Vol.76, 1986, 393-8.

Vickers, John. "The Evolution of Market Structure When There is a Sequence of Innovations." *The Journal of Industrial Economics*, Vol.35, 1986, 1-12.