Working Paper 94-33
Economics Series 15
October 1994

Departamento de Economía
Universidad Carlos III de Madrid
Calle Madrid, 126
28903 Getafe (Spain)
Fax (341) 624-9875

TECHNOLOGY DIFFUSION IN A DIFFERENTIATED INDUSTRY

Emmanuel Petrakis*

Abstract

This paper investigates the adoption timing pattern of a cost-reducing innovation in a differentiated oligopolistic industry. It compares price and quantity market competition with the second-best optimal adoption rule. The diffusion pattern typically depends on the degree of product differentiation, and on the ability of firms to precommit, or not, to a certain adoption date. When goods are imperfect substitutes, market competition leads always to later adoption dates than it is socially optimal. When goods are sufficiently close substitutes the last adoption occurs always earlier than in the optimum; the first adoption might also occur earlier but only if preemption is a credible threat.

Keywords
Innovation, Diffusion, Horizontal Differentiation, Imperfect Competition.

*Departamento de Economía, Universidad Carlos III de Madrid, Calle Madrid 126, 28903 Getafe, Spain. e-mail: petrakis@elrond.uc3m.es. I would like to thank H. Bester and D. Pérez Castrillo for helpful comments as well as the audiences of the IX Jornadas de Economía Industrial 1993 in Madrid, the EARIE 1994 Conference in Chania, Crete, and the ASSET 1994 Meetings in Lisbon where earlier versions of this paper were presented.

1 Introduction

Technological progress is the leading force of economic growth. For technological progress to occur basic research discoveries are necessary but not sufficient. The follow-up stage of development of an innovation is equally important. Often basic research is conducted in non-profitable institutions (e.g. universities, state research centres etc.) and its discoveries become available at some price. Their development is usually left to market forces that are motivated by their own interests. Bringing a new technology on line is costly for a firm. However, this cost may decline significantly as the development horizon becomes longer due to either economies of learning or basic research adoption process innovations.

This paper studies the incentives to develop a new cost-reducing technology in a differentiated oligopolistic industry. Two firms, competing either in prices or in quantities in the product market, decide on when to adopt a new technology which is available to them at time 0. Both firms initially have constant per unit cost of c. A firm that adopts the new technology reduces its per unit cost by Δ. The cost of purchasing and bringing the technology on line, which initially is prohibitively high for an immediate adoption to be profitable, falls significantly over time. Firms face symmetric linear demand conditions for their differentiated products.

The existing literature (Reinganum (1981a&b, 1983), Fudenberg & Tirole (1985), Quirmbach (1986)) has focused on a homogeneous industry where typically firms compete in quantities. Reinganum (1981a, 1983) provides conditions under which the new technology is diffused over time in a duopoly with long information lags where each firm can safely <u>precommit</u> to a specific adoption date. Fudenberg & Tirole (1985) consider the opposite extreme where firms can observe and react instantaneously to their rivals' adoptions. Firms' profits are equalized in equilibrium because each firm adopts preemptively to prevent, or delay, adoption by its opponent. Quirmbach (1986) compares the diffusion rates in alternative specifications of the innovation market (given that firms compete in quantities in the product market) and shows that in a precommitment equilibrium the rate of diffusion is faster in market structure A than in B if and only if the incremental benefits of adopting the new technology are larger in A than in B. (Reinganum (1989) provides an excellent survey of the literature on the timing of adoption).

We consider two alternative specifications of the product market, a price-setting and a quantity-setting game. By considering a differentiated industry we are able to explore the impact of product differentiation on the rate of diffusion of the new technology. Analyzing both the precommitment and the preemptive equilibria of the adoption game, we investigate the extent to which diffusion rates depend on the flexibility a firm has in altering its plans of implementation of the new technology. We compare the market diffusion rates with the second-best optimal rates, i.e. when the social planner takes the product market structure as given. Also, the adoption timing patterns under Bertrand and Cournot competition are compared. By convention firm-1 always adopts first, and firm-2 second.

We find that under Cournot or Bertrand, in both precommitment and preemptive equilibria, for a sufficiently high degree of substitutability firm-2 adopts the new technology earlier in the market than it should optimally do. In a precommitment equilibrium, Cournot or Bertrand, firm-1 always adopts later than under the optimum. However, in a preemptive equilibrium this result can be reversed if the goods are sufficiently close substitutes. Note, the quantifier "sufficiently" in the results stated depends, both on the type of market competition and on the type of equilibrium of the adoption game.

These results suggest that policy measures ought to be designed carefully to correct the dynamic inefficiencies introduced by the market imperfections. In policy design all of the following factors should be taken into account: (i) the type of market competition, (ii) the degree of product differentiation, (iii) the degree of firm´s flexibility to alter its adoption plans in response to its rival´s past actions, (iv) the size of the market, and finally (v) how drastic the innovation is. Subsidizing the firm that adopts the new technology first turns out to be a welfare-improving measure only if altering the adoption plans is very costly. However, if these costs are low enough, taxing the new technology can improve welfare if the firm´s good has sufficiently close substitutes in the market. On the other hand, subsidizing the firm that adopts second is welfare improving only if the goods are sufficiently poor substitutes.

Finally, it is shown that in both precommitment and preemptive equilibria Cournot firm-2 always adopts earlier than Bertrand firm-2. Also, in a precommitment equilibrium Bertrand firm-1 adopts earlier than its Cournot counterpart if the goods are sufficiently close substitutes. The opposite is true for lower values of substitutability. However, in a preemptive equilibrium Bertrand firm-1 adopts <u>always</u> earlier than Cournot firm-1.

The paper is organized as follows. Section 2 presents the model and outlines the basic assumptions. It also analyzes the per-period product market competition under cost asymmetries. In section 3 the second-best adoption timing pattern is derived. In section 4 the adoption dates in a precommitment equilibrium are computed when firms are either competing a lá Cournot or a lá Bertrand in the product market. Section 5 compares the market adoption pattern against the optimal one; it also compares the adoption dates in a Cournot industry with those in a Bertrand. In sections 6 and 7 we derive the adoption dates in a preemptive equilibrium, and compare them with the optimal ones. Section 8 is the conclusion.

2 The Model

We consider an economy with an oligopolistic sector, consisting of two firms that produce a differentiated good, and a competitive numeraire sector. The two firms operate under constant returns to scale and have initially the same unit cost of production c. At $t=0$ a cost reducing innovation is announced and offered for sale in the market. A firm can purchase the new technology at any $t \geq 0$ and reduce thereafter its unit cost to $c-\Delta$, $0 < \Delta < c$. Let $k(t)$ be the present value of the costs of purchasing and bringing the innovation on line at time t. Following Fudenberg & Tirole (1985) we assume that the "current cost" $k(t)e^{rt}$ is decreasing over time, at a decreasing rate, that is, $(k(t)e^{rt})' < 0$ and $(k(t)e^{rt})'' > 0$, where r is the interest rate, $0 < r < 1$. The costs can decline as the development horizon becomes longer due to either economies of learning or new results from basic research that facilitate the adoption process. Assume further that (a) $\lim_{t \to 0} k(t) = -\lim_{t \to 0} k'(t) = \infty$. This is a sufficient condition for immediate adoption to be prohibitively costly under any circumstances; and (b) $\lim_{t \to \infty} k'(t)e^{rt} = 0$. This condition guarantees that all adoptions occur in finite time under all parameter constellations. The latter assumption is not crucial for our results; it only serves to avoid the complications which create corner solutions. Finally, we introduce a simplifying assumption that no further innovation is anticipated in the industry.

The market operates every period $t \geq 0$. The market demand structure is the same in each period t, and follows Dixit (1979). The representative consumer´s utility over the two (non-durable) differentiated goods (x_1, x_2) and the numeraire (non-durable) good m is given by

$$U(x_1, x_2) = a(x_1 + x_2) - (x_1^2 + 2\gamma x_1 x_2 + x_2^2)/2 + m \qquad (1)$$

where $a > c$ and $0 < \gamma < 1$. The assumption that utility is linear in the numeraire good eliminates income effects and allows us to perform partial equilibrium analysis. The specification of $U(.)$ generates a linear symmetric demand structure,

$$p_1 = a - x_1 - \gamma x_2 \qquad\qquad p_2 = a - x_2 - \gamma x_1 \tag{2}$$

which permits us to study how the adoption timing of the new technology depends upon the substitutability of the two goods. The latter is measured by the parameter γ. As γ increases the goods become better substitutes, and for $\gamma=1$ they are perfect substitutes. As γ goes to zero, each firm becomes virtually a monopolist for its product.

We first analyze the case of Cournot competition. Given the demand system (2) and its own cost c_i, firm i chooses its quantity x_i to maximize profits $[p_i - c_i]x_i$ taking the quantity produced by its competitor x_j as given. This results in the equilibrium quantities (x_1^C, x_2^C) where

$$x_i^C(c_i, c_j) = [2(a - c_i) - \gamma(a - c_j)]/(4 - \gamma^2) \qquad i,j = 1,2 \tag{3}$$

The adoption of the cost-reducing technology from firm i increases x_i^C and decreases x_j^C. This latter effect is strategically advantageous for firm i because from (2) its own price is negatively related with firm j's quantity. Thus quantity competition creates a *positive strategic effect* to innovate. To avoid corner solutions we restrict attention to the range of the substitutability parameter where both firms are active in the market. From (3), this is the case if and only if $\gamma<\gamma_C(\Delta)$, where $\gamma_C(\Delta) \equiv min[1, 2(a-c)/(a-c+\Delta)]$. Finally, using the first order conditions, the per-period profits are given by

$$\pi_i^C(c_i, c_j) = [x_i^C(c_i, c_j)]^2 \qquad i,j=1,2 \tag{3$'$}$$

We next turn to the case of Bertrand competition. By inverting (2) we obtain the demand functions

$$x_1 = [(a - p_1) - \gamma(a - p_2)]/(1-\gamma^2); \quad x_2 = [(a - p_2) - \gamma(a - p_1)]/(1-\gamma^2) \tag{4}$$

Firm i chooses its price p_i to maximize its profits $[p_i - c_i]x_i$ taking the competitor's price p_j

as fixed. This generates the equilibrium prices (p_1^B, p_2^B) given by

$$p_i^B(c_i, c_j) = [(2+\gamma)(1-\gamma)a + 2c_i + \gamma c_j]/(4 - \gamma^2) \quad i,j = 1,2 \tag{5}$$

When firm i adopts the cost-reducing technology both p_i^B and p_j^B decrease. The latter is disadvantageous for firm i, because its output is positively related with p_j. In contrast with Cournot, Bertrand competition creates a *negative strategic effect*. Now, does this imply that firms competing in prices always adopt the technology later than if they compete in quantities? As we will see, the answer is no. As in Bester & Petrakis (1993) there is an additional effect, *the market share effect*, which plays an important role. If the cost-reducing technology sharply increases its market share, there are stronger incentives for the firm to adopt the technology earlier since the cost reduction applies to a higher volume of production.

As previously, we restrict ourselves to parameter values for which both firms operate in the market. This happens if and only if $p_i^B(c_i, c_j) > c_i$. From (5) this holds if $\gamma < \gamma_B(\Delta)$, where $\gamma_B(\Delta)$ is implicitly defined by $\gamma_B(\Delta) \equiv \gamma_C(\Delta)[2-\gamma_B^2(\Delta)]/2$. Thus $\gamma_B(\Delta) < \gamma_C(\Delta)$. Finally, using the first order conditions, the flow of profits is given by

$$\pi_i^B(c_i, c_j) = [p_i^B(c_i, c_j) - c_i]^2/(1-\gamma^2) \qquad i,j=1,2 \tag{5'}$$

3 The Second-Best Adoption Pattern

We first investigate the (second-best) optimal adoption pattern of the new technology from the viewpoint of social welfare. Let V_0^m, V_1^m, and V_2^m, be the per-period total welfare if none, only one, or both firms adopt the new technology in the market m. By convention firm-1 always adopts first in the sequel. The social planner, taking the market structure as given, chooses the adoption pattern (T_1^{Sm}, T_2^{Sm}) so as to maximize

$$W(T_1,T_2) = \int_0^{T_1} V_0^m e^{-rt}dt + \int_{T_1}^{T_2} V_1^m e^{-rt}dt + \int_{T_2}^{\infty} V_2^m e^{-rt}dt \ -k(T_1)-k(T_2) \tag{6}$$

where $V_0^m = V^m(c,c)$, $V_1^m = V^m(c-\Delta,c)$, and $V_2^m = V^m(c-\Delta,c-\Delta)$ with

$$V^m(c_1,\ c_2) \equiv U(x_1^m(c_1,\ c_2),\ x_2^m(c_1,\ c_2)) - c_1 x_1^m(c_1,\ c_2) - c_2 x_2^m(c_1,\ c_2) \tag{7}$$

m can be either a Cournot (C) or a Bertrand market (B). The first order conditions from (6) determine the optimal adoption pattern according to

$$\begin{aligned} V_1^m - V_0^m &= -k'(T_1^{Sm})e^{rT_1^{Sm}} \\ V_2^m - V_1^m &= -k'(T_2^{Sm})e^{rT_2^{Sm}} \end{aligned} \tag{8}$$

Let $I_1^{Sm} \equiv V_1^m - V_0^m$, and $I_2^{Sm} \equiv V_2^m - V_1^m$ be the social planner´s incremental benefits from firm-1´s, and -2´s adoption respectively. Substituting (3) into (7) we obtain the incremental benefits in case that the firms compete a la Cournot

$$I_1^{SC} = \Delta\ [2(3+\gamma)(a-c)(2-\gamma)^2 + (12-\gamma^2)\Delta]/2(4-\gamma^2)^2 \tag{9}$$

$$I_2^{SC} = \Delta\ [2(3+\gamma)(a-c)(2-\gamma)^2 + (12-16\gamma-\gamma^2+2\gamma^3)\Delta]/2(4-\gamma^2)^2 \tag{10}$$

Further, substituting (5) into (4) and using (7) we obtain the corresponding expressions for the case of Bertrand competition

$$I_1^{SB} = \Delta[2(3-2\gamma)(a-c)(1-\gamma)(2+\gamma)^2 + (12-9\gamma^2+2\gamma^4)\Delta]/2(1-\gamma^2)(4-\gamma^2)^2 \tag{11}$$

$$I_2^{SB} = \Delta[2(3-2\gamma)(a-c)(1-\gamma)(2+\gamma)^2 + (12-16\gamma-9\gamma^2+6\gamma^3+2\gamma^4)\Delta]/2(1-\gamma^2)(4-\gamma^2)^2 \tag{12}$$

Then $I_i^{Sm} > 0$, $i=1,2$ and $I_1^{Sm} > I_2^{Sm}$, $m=B,C$ for all $0<\gamma<1$ and $\Delta>0$. From (8), T_i^{Sm} depends only on I_i^{Sm}. It follows that $T_1^{Sm} < T_2^{Sm}$ as $[-k'(t)e^{rt}]$ is decreasing in t. Hence diffusion of the new technology results from a pattern of decreasing incremental benefits as is pointed out in Quirmbach (1986).

4 The Precommitment Equilibrium

In this section we study the "two-stage" game where at the beginning of their planning horizon firms precommit simultaneously to specific adoption dates. The firms then compete in the product market each period over an infinite horizon. In this context "adoption date" represents the time by which the adoption has been completed. To bring the new technology on line a firm often has to make long term plans. These plans can be altered later only at high expenses. Precommitment at time 0 is a time consistent behaviour only if the costs of altering the adoption plans are prohibitively high. That is, the threat of altering one´s adoption date as a response to the rival´s past actions is not credible.

Let π_0^m, π_2^m be the per-period profits when none, or both firms have adopted the new technology. Also, π_ℓ^m, π_f^m be the per-period profits of the leader (firm that has already adopted), and the follower (that has not yet adopted), $m=C,B$. Then $\pi_0^m=\pi^m(c,c)$, $\pi_2^m=\pi^m(c\text{-}\Delta,c\text{-}\Delta)$, $\pi_\ell^m=\pi_1^m(c\text{-}\Delta,c)$ and $\pi_f^m=\pi_2^m(c\text{-}\Delta,c)$. At time 0 firm i, $i=1,2$ chooses T_i^m to maximize its discounted sum of profits

$$\begin{aligned} \Pi_1^m(T_1,T_2) &= \int_0^{T_1}\pi_0^m e^{-rt}dt + \int_{T_1}^{T_2}\pi_\ell^m e^{-rt}dt + \int_{T_2}^{\infty}\pi_2^m e^{-rt}dt - k(T_1) \\ \Pi_2^m(T_1,T_2) &= \int_0^{T_1}\pi_0^m e^{-rt}dt + \int_{T_1}^{T_2}\pi_f^m e^{-rt}dt + \int_{T_2}^{\infty}\pi_2^m e^{-rt}dt - k(T_2) \end{aligned} \tag{13}$$

The first order conditions of (13) are as follows

$$\begin{aligned} \pi_\ell^m - \pi_0^m &= -k'(T_1^m)e^{rT_1^m} \\ \pi_2^m - \pi_f^m &= -k'(T_2^m)e^{rT_2^m} \end{aligned} \tag{14}$$

Let $I_1^m=\pi_\ell^m\text{-}\pi_0^m$, and $I_2^m=\pi_2^m\text{-}\pi_f^m$. I_i^m is then firm i´s incremental benefit from adoption in the market m. Then from (3) and (3)′ we obtain the incremental benefits of firm-1, and -2 in the Cournot market

$$I_1^C = 4\Delta[(a-c)(2-\gamma)+\Delta]/(4-\gamma^2)^2 \qquad (15)$$

$$I_2^C = 4\Delta[(a-c)(2-\gamma)+\Delta(1-\gamma)]/(4-\gamma^2)^2 \qquad (16)$$

Also, from (5) and (5)′ we get the corresponding expressions for the Bertrand market

$$I_1^B = \Delta(2-\gamma^2)[2(a-c)(1-\gamma)(2+\gamma)+\Delta(2-\gamma^2)]/(1-\gamma^2)(4-\gamma^2)^2 \qquad (17)$$

$$I_2^B = \Delta(2-\gamma^2)[2(a-c)(1-\gamma)(2+\gamma)+\Delta(2-\gamma^2-2\gamma)]/(1-\gamma^2)(4-\gamma^2)^2 \qquad (18)$$

Thus $I_i^m > 0$ and $I_1^m > I_2^m$ for all $\Delta > 0$ and $0 < \gamma < 1$ in both markets. Further, by (14) T_i^m depends only on I_i^m and by our assumption on $k(.)$ we get $T_1^m > T_2^m$ for $m=B,C$. As Quirmbach (1986) noted the diffusion of new technology in the market is not due to strategic behaviour, but rather to a pattern of decreasing incremental benefits. In addition, it becomes clear from (8) and (14) that to compare adoption timing in various contexts it is sufficient to compare their respective incremental benefits. This is the task of the following section.

5 Adoption Timing in the Precommitment Equilibrium

We start by comparing the (second-best) optimal adoption pattern with those evolving in the market. Surprisingly, the qualitative features of this comparison are similar for both markets, despite the fact that the adoption of technology creates a positive strategic effect in the Cournot market, while a negative strategic effect in the Bertrand market. Thus, independent of the market, we have

Proposition 1: *In a Precommitment equilibrium, $T_1^{Sm} < T_1^m$, $m = C,B$, for all γ and Δ. Thus the Social Planner must <u>always</u> subsidize firm-1 in the market if the costs of altering adoption plans are very high.*

Proof: From (9) and (15), $I_1^{SC} > I_1^C$ if and only if $[2(1-\gamma)(a-c)+\Delta]\Delta/2(4-\gamma^2) > 0$. This is true for all $0<\gamma<1$ and $\Delta>0$. Also, from (11) and (17), $I_1^{SB} > I_1^B$ if and only if $[2(1-\gamma)(a-c)+\Delta]\Delta/2(4-\gamma^2)(1-\gamma^2) > 0$, which is again always true. Then (8) and (14) imply that $T_1^{Sm} < T_1^m$, $m=C, B$, because $-k'(t)e^{-rt}$ is decreasing in t. Q.E.D.

Our first result says that firm-1 always adopts the new technology too late in comparison with the optimal date of adoption. In the market firm-1 cannot appropriate the full social surplus generated by the adoption, so it prefers to wait a little longer when the costs of bringing the new technology on line become lower. This is related to Dasgupta & Stiglitz (1980) observation that non-appropriability of social surplus leads to underinvestment relative to the social optimum. Thus, whenever there are significant costs for altering adoptions plans, subsidizing firm-1's adoption is a welfare-improving policy regardless of the type of market competition. However, the optimal amount of the (lump-sum) subsidy depends on the type of competition, the degree of product differentiation (decreasing in γ), on how drastic the innovation is (increasing in Δ), and on the size of the market (increasing in a).

Let $\gamma^{\#}(\Delta) \equiv [2(a-c)+\Delta]/2(a-c+\Delta)$. Then $\gamma^{\#}(\Delta) < \gamma_B(\Delta)$ if $\Delta < 0.781(a-c)$. This condition is satisfied whenever the market is not too small. Then firm-2 might adopt earlier or later than it is socially optimal depending on how close substitutes the goods are:

Proposition 2: *In a precommitment equilibrium, for each $\Delta < 0.781(a-c)$ there is a $\gamma^{\#}(\Delta)$ such that $T_2^{Sm} < T_2^m$ if $\gamma < \gamma^{\#}$, and $T_2^{Sm} > T_2^m$ if $\gamma > \gamma^{\#}$, $m=B,C$. Moreover, $\gamma^{\#}(.)$ decreases with Δ. Thus the Social Planner has to tax firm-2 if the goods are close enough substitutes, but subsidize it otherwise, in case that the cost of altering adoption plans is very high.*

Proof: From (10) and (16), $I_2^{SC} > I_2^C$ if and only if $[(a-c)+(1-2\gamma)(a-c+\Delta)]\Delta/2(4-\gamma^2) > 0$, which is true for $\gamma < \gamma^{\#}(\Delta)$. Also, from (12) and (18), $I_2^{SB} > I_2^B$ if and only if $[(a-c)+(1-$

$2\gamma)(a-c+\Delta)]\Delta/2(4-\gamma^2)(1-\gamma^2)>0$, which is again true for $\gamma<\gamma^{\#}(\Delta)$. Then (8) and (14) imply that $T_2^{Sm}<T_2^m$ if $\gamma<\gamma^{\#}(\Delta)$, and $T_2^{Sm}>T_2^m$ otherwise. Q.E.D.

If the goods are sufficiently close substitutes, firm-2 adopts the new technology earlier in the market (Cournot or Bertrand) than in the optimum. The reverse, however, is true if the goods are poor substitutes. Surprisingly, the social planner does not have to look at the type of competition when choosing between taxing or subsidizing firm-2: the critical value of γ, $\gamma^{\#}$, is the same for both markets. Yet, the optimal adoption tax/subsidy depends on the complete list of the parameters: market size, degree of differentiation, drasticity of innovation, and type of market competition.

The intuition behind the above result is as follows. For low values of γ firm-2 is almost a monopolist in the market, so it cannot appropriate the full social surplus generated by the cost-reducing innovation. Thus it will wait relatively longer for the costs of bringing the innovation on line to decrease sufficiently to compensate for the part of social surplus which it cannot appropriate.

However, if γ is sufficiently close to γ_m, $m=B,C$ firm-2 hardly produces anything before adoption. Given that almost all production is already done by firm-1 with the low cost technology, and that the goods are close substitutes, the adoption of the innovation by firm-2 increases the social surplus very little. The cost-reducing technology would only apply to a tiny production share which firm-2 had. On the other hand, innovation increases significantly firm-2's share in the market, thus creating a strong incentive to adopt the new technology earlier. This business-stealing effect dominates the non-appropriability effect for γ sufficiently high and so firm-2 in the market adopts earlier than in the second-best optimum.

A better insight on why the critical value of γ, $\gamma^{\#}$, is the same in both markets despite the fact that the strategic effects work in opposite directions (positive in quantity competition, but negative in price competition) can be gained by comparing the adoption timing pattern of Cournot and Bertrand markets. Let $\hat{\gamma}(\Delta) \equiv 2(a-c)/[2(a-c)+\Delta]$. It can be easily checked that $\hat{\gamma}(\Delta) < \gamma_B(\Delta)$ for all Δ. We have the following result:

Proposition 3: *Let $\gamma < \gamma_B(\Delta)$. Then in a precommitment equilibrium*

(i) For each Δ there is a $\hat{\gamma}(\Delta)$ such that $T_1^C < T_1^B$ for $\gamma < \hat{\gamma}$ and $T_1^C > T_1^B$ for $\gamma > \hat{\gamma}$. Moreover, $\hat{\gamma}(.)$ is decreasing in Δ.

(ii) $T_2^C < T_2^B$ for all γ.

Proof: From (15) and (17), $I_1^C > I_1^B$ if and only if $[(2-\gamma)(a-c)-\gamma(a-c+\Delta)]\gamma^3\Delta/(1-\gamma^2)(4-\gamma^2)^2 > 0$, or equivalently if $(a-c)/(a-c+\Delta) > \gamma/(2-\gamma)$, which is true if $\gamma < \hat{\gamma}(\Delta)$. Also from (16) and (18), $I_2^C > I_2^B$ if and only if $[2(1-\gamma)(a-c)+(2-\gamma)\Delta]\gamma^3\Delta/(1-\gamma^2)(4-\gamma^2)^2 > 0$ which is true always. Then by (14) we obtain the result. Q.E.D.

The intuition for part (i) is that for low values of γ the difference in the strategic effect under Cournot and Bertrand competition is dominant. While as γ increases the *market share effect* (Bester & Petrakis (1993)) becomes more important. In fact, when the two commodities are poor substitutes their demands are hardly related, so a firm´s output hardly differs in the two types of market. Thus total cost reduction due to adoption is of the same magnitude in both Bertrand and Cournot markets. However, for low values of γ the innovation is more profitable for a Cournot firm-1 because it decreases firm-2´s output whereas for a Bertrand firm-1 it decreases its competitor´s price. Therefore a Bertrand firm-1 will adopt in a later moment when the costs of bringing the technology on line are lower.

On the other hand, when the goods are very close substitutes, a cost-reducing innovation has a significant impact on the firm´s market share. Especially, if γ is close enough to $\gamma_B(\Delta)$, adoption of the new technology from firm-1 reduces firm-2´s market share to almost zero. In Cournot competition firm-2´s reduction of market share is much less drastic, because $\gamma_B(\Delta) < \gamma_C(\Delta)$ implies that firm-2 has a "decent" market share even after firm-1's innovation. Therefore for high values of γ the Bertrand market creates a stronger incentive for firm-1 to innovate than the Cournot market. The market share effect dominates and firm-1 adopts earlier in price competition.

Part (ii) of Proposition 3 tells us that a Cournot firm-2 always adopts earlier than its Bertrand counterpart. The strategic effect dominates the market share effect for all substitutability values. For low values of γ the intuition is given above. But for high γ it is the strength of price competition which diminishes the market share effect. Firm-2's after-adoption profits do not increase much, even if its market share do increase a lot. This is due to the fierce competition between firms that are producing very similar goods. The after-innovation competition is much softer for a Cournot firm-2, thus its profits increase sufficiently despite the fact that its market share increases much less than Bertrand firm-2's.

6 The Preemptive Equilibrium

If adoption is perfectly observable and instantaneous, and if the costs of altering adoption plans are not significant (Fudenberg & Tirole (1983)), a firm cannot credibly commit to maintain its adoption date regardless of what happened in the past. In a precommitment equilibrium firm-1 that innovates first makes higher profits than firm-2 that adopts later. However, if preemption is possible this cannot happen. Firm-2 would have incentive to adopt the new technology just before firm-1 in order to increase its profits. Firm-1, facing preemption, will then innovate at an earlier moment such that firm-2 is indifferent between adopting just before that moment and adopting much later. Thus, in a preemptive equilibrium the *Rent Equalization Principle* holds.

The specification of the game is the same as section 4 except that history matters. As a result we need to look for time consistent innovative behaviour. Once firm-1 has adopted the new technology, firm-2's adoption is a one-player decision problem. it chooses τ_2^m to maximize its profits $\Pi_2^m(T_1, T_2)$ (given in (13)) with the only restriction that $\tau_2^m \geq \tau_1^m$. The first-order condition of this problem is the same as in the precommitment equilibrium, and is given by (14) with τ_2^m replacing T_2^m. Given our assumption that firm-2 always adopts later, this implies that in both a preemptive and a precommitment equilibrium firm-2 adopts the same time, i.e. $\tau_2^m = T_2^m$ for $m = C,B$.

From the Rent Equalization Principle we determine τ_1^m by equating the discounted sum of profits, i.e. $\Pi_1^m(\tau_1^m, \tau_2^m) = \Pi_2^m(\tau_1^m, \tau_2^m)$. From (13) and after some manipulations we get

$$\pi_\ell^m - \pi_f^m = r\frac{k(\tau_1^m) - k(\tau_2^m)}{e^{-r\tau_1^m} - e^{-r\tau_2^m}} \tag{19}$$

where π_ℓ^m and π_f^m are the leader's and follower's flow of profits, respectively, in market m, $m=C,B$. Note, given $\tau_2^m = T_2^m$ firm-1's optimal adoption date depends only on the differential of the per-period profits of being the leader and being the follower. Following Katz & Shapiro (1987), we call this firm-1's *preemptive incentive*. A comparison of the preemptive incentives created by Bertrand and Cournot markets are given in the following proposition.

Proposition 4: *For all $\gamma < \gamma_B(\Delta)$ the preemptive incentives in Bertrand and Cournot markets are equal, i.e.* $\pi_\ell^C - \pi_f^C = \pi_\ell^B - \pi_f^B$.

Proof: Using (3), (3)', (5) and (5)', we have $\pi_\ell^C - \pi_f^C = [2(a-c)+\Delta]\Delta/(4-\gamma^2) = \pi_\ell^B - \pi_f^B$.

Q.E.D.

This result seems to be specific to the linear demand structure. Nevertheless, it suggests that the preemptive incentives in Cournot and Bertrand competition are often of similar magnitude in a broader class of demand conditions. The intuition is that for fixed γ, the Bertrand market is more competitive than the Cournot market. This suggests a larger profit differential between the low-cost leader and the high-cost follower in the Bertrand market. However, the leader's adoption generates positive externalities for the follower in the Bertrand market, but negative externalities in the Cournot market. The latter counterbalances the competitiveness effect.

7 Adoption Timing in the Preemptive Equilibrium

From the previous section we know that firm-2 adopts at the same time in both the precommitment and the preemptive equilibria. In section 5 we found that

(i) Cournot firm-2 always adopts earlier than its Bertrand counterpart, and

(ii) For sufficiently high values of γ firm-2 in the market adopts earlier than in the second best optimum. The reverse is true for low values of substitutability.

Let us first compare firm-1's optimal adoption date in a price-setting and a quantity-setting game. Let,

$$f(t_1,t_2) = \frac{k(t_1) - k(t_2)}{e^{-rt_1} - e^{-rt_2}} \tag{20}$$

Proposition 5: *In a preemptive equilibrium, $\tau_1^B < \tau_1^C$ for all γ* and Δ.

Proof: Let $g(t)=k(t)e^{rt}$. By assumption $g(t)$ is strictly decreasing and strictly convex. Differentiating (20) we have

$$\frac{\partial f(t_1,t_2)}{\partial t_1} = \frac{e^{-r(t_1+t_2)}[g'(t_1)(e^{r(t_2-t_1)}-1)+r(g(t_1)-g(t_2))]}{(e^{-rt_1}-e^{-rt_2})^2} \tag{21}$$

By strict convexity of $exp(x)$ we have $exp[r(t_2-t_1)]-1 > r(t_2-t_1)$. As $g(t)$ is decreasing and strictly convex, the right hand term of (21) in square brackets $[..] < r\{g'(t_1)(t_2-t_1) + (g(t_1)-g(t_2))\} < 0$. Thus, $f(t_1, t_2)$ is decreasing in t_1. and in t_2 by the symmetry of (20). Hence, $\tau_2^B > \tau_2^C$ implies $f(t_1, \tau_2^B) < f(t_1, \tau_2^C)$. Then from (19) and proposition 4 we have $\tau_1^B < \tau_1^C$. Q.E.D.

Firm-1 in a Bertrand market always adopts the new technology earlier than its counterpart in a Cournot market. In fact, firm-1 under price competition enjoys the leadership longer than under quantity competition. Given that the preemptive incentives per-period are the same in both markets, firm-1 has a stronger overall incentive to preempt in a Bertrand than in a Cournot market.

Finally, we compare firm-1's adoption decision in the market with the second-best optimum. We know that for $m=C,B$,

$$\pi_l^m - \pi_f^m = \Delta[2(a - c) + \Delta]/(4 - \gamma^2) \tag{22}$$

Hence firm-1's preemptive incentive increases as the two goods become better substitutes. Further, from (16) and (18), I_2^m is decreasing in γ for all Δ in Bertrand and for sufficiently high Δ in Cournot competition. This implies that T_2^m is typically increasing in γ. The closer substitutes the two goods are, the later firm-2 adopts the new technology in the market. This in turn implies that $f(t,.)$ decreases with γ and given that the preemptive incentives increase with γ, firm-1 adopts earlier as the goods become better substitutes. On the other hand, I_1^{Sm} is decreasing in γ for all Δ in Bertrand and for small enough Δ in Cournot. Thus as the goods become closer substitutes the social planner usually postpones adoption for later. The above analysis leads us to the following conjecture: Firm-1 in the market may adopt earlier than in the second-best optimum when the goods are sufficiently close substitutes and the innovation is sufficiently drastic. This is in fact the case as the following example show.

Example 1: Let $k(t)=e^{-(\alpha+r)t}$, where $\alpha=2$ and $r=.1$. Let $a=10$, $c=4$. If $\gamma=.9$ and $\Delta=.5$, then the optimal adoption pattern in case that firms compete a la Cournot is $T_1^{SC}=0.153$, $T_2^{SC}=0.214$, while firm-1, and -2 adopt the new technology at $T_1^C=0.204$ and $T_2^C=0.237$ respectively in the precommitment market equilibrium. In the preemptive market equilibrium, however, firm-1 adopts immediately ($\tau_1^C=0$). A similar result holds for the Bertrand market: $T_1^{SB}=0.036$, $T_2^{SB}=0.237$, while in the precommitment equilibrium $T_1^B=0.2578$ and $T_2^B=0.383$. Again firm-1 adopts immediately ($\tau_1^B=0$) in the preemptive equilibrium. Note, that adoption in period 0 results here because our assumption that immediate adoption is prohibitively costly does not hold.

8 Conclusion

By studying a differentiated oligopolistic industry where firms compete either in prices or in quantities, this paper increases our understanding on how product market competition influences the private and public incentives to adopt a new technology. It develops a framework where market adoption timing patterns can be compared with the (second-best) optimal patterns. This provides further insights for the design of a technology policy aiming at correcting the inefficiencies of the laissez-faire. The degree of product differentiation turns out to be an important factor in this comparison. For example, subsidizing the firm that adopts second is a welfare-improving policy if its commodity has only poor substitutes in the market, while taxing adoption is optimal otherwise. An equally important factor is the firm's flexibility to alter its adoption plans as a reaction to its rival's past actions. If the goods are good substitutes, the policymaker may have to tax the first firm that innovates in case that the costs of altering adoption plans is low, but to subsidize it if the firm can precommit to a specific adoption date.

In addition, it is shown that the optimal tax/subsidy on the adoption of a new technology is very sensitive to all market parameters. The type of competition (Bertrand or Cournot), the demand conditions (e.g. size of the market), the drasticity of the innovation and the rate of decrease of adoption costs, besides the ones mentioned above, have to be taken into account while designing technology policy. Some other factors, not considered in this paper, but which have been shown in the literature to be equally important for the technology policy are: Uncertainty about the innovation´s profitability or the length of time required for its successful implementation (Reinganum (1983a, 1983b), Stenbacka & Tombak (1994)), price and entry regulations (Riordan(1992)), and possibilities of imitation and licensing (Katz & Shapiro(1987)). Introducing one or more of these factors into our more general framework will provide further insights into the design of the technology policy, a task left for future research.

REFERENCES

Bester, H., and E. Petrakis (1993): " The Incentives for Cost Reduction in a Differentiated Industry", *International Journal of Industrial Organization*, 11, 519-534.

Dasgupta, P., and J. Stiglitz (1980): "Uncertainty, Industrial Structure and Speed of R&D", *The Bell Journal of Economics*, 90, 1-28.

Dixit, A. (1979): "A Model of Duopoly Suggesting a Theory of Entry Barriers", *Bell Journal of Economics*, 10, 20-32.

Fudenberg, D., and J. Tirole (1985): "Preemption and Rent Equalization in the Adoption of New Technology", *Review of Economic Studies*, 52, 383-401.

Katz, M., and C. Shapiro (1987): " R&D Rivalry with Licensing or Imitation", *American Economic Review*, 77, 402-420.

Quirmbach, H. (1986): "The Diffusion of New Technology and the market for an Innovation", *Rand Journal of Economics*, 17, 33-47.

Reinganun, J. (1981a): "On the Diffusion of New Technology: A Game Theoretic Approach", *Review of Economic Studies*, 48, 395-405.

Reinganum, J. (1981b): "Market Structure and the Diffusion of New Technology", *Bell Journal of Economics*, 12, 618-624.

Reinganum, J. (1983a): "Technology Adoption under Imperfect Information", *Bell Journal of Economics*, 14, 57-69.

Reinganum, J. (1983b): "Uncertain Innovation and the Persistence of Monopoly", *American Economic Review*, 73, 741-748.

Reinganum, J. (1989): "The Timing of Innovation: Research, Development, and Diffusion", *Handbook of Industrial Organization*, Vol. 1, R. Schmalensee and R. Willig (eds.), North Holland, Amsterdam.

Riordan, M. (1992): "Regulation and Preemptive Technology Adoption", *RAND Journal of Economics*, Vol. 23, 334-349.

Stenbacka, R., and M. Tombak (1994): "Strategic Timing of Adoption of New Technologies under Uncertainty", *International Journal of Industrial Organization* (forthcoming).