Growth with Non-Drastic Innovations and the Persistence of Leadership

Vincenzo Denicolò*

Dipartimento di Scienze Economiche, Università di Bologna

Abstract

In a model of endogenous growth with improvements in the quality of products, I provide a new explanation of the persistence of leadership by assuming that innovations are non-drastic and that the current leader has a move advantage in the next patent race. Under these circumstances, the value of being leader exceeds temporary monopoly profit, since the leader reaps an extra-profit in the next patent race despite free entry by outsiders. This will increase the incentive to innovate and hence the rate of growth, which is higher than in the leapfrogging model. However, the welfare comparison of the leapfrogging and persistent-leadership equilibria is ambiguous.

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* Piazza Scaravilli 2, I-40125 Bologna, Italy; E-mail: denicolo@economia.unibo.it

1. INTRODUCTION

In early models of endogenous growth with quality ladders (see Aghion and Howitt, 1992, Segerstrom, Anant and Dinopoulos, 1990, and Grossman and Helpman, 1991) the current technological leader does no research and is systematically replaced by outsiders. This pattern of leapfrogging is evidently unrealistic. Not only do incumbents often maintain their market shares for a long time; there is also ample evidence that they tend to account for much of the research done, either performing it directly in-house or else, indirectly, acquiring intellectual property rights from independent inventors.

Previous attempts to explain the persistence of leadership either assume that the leader is more efficient than outsiders in conducting the research, as in Barro and Sala-i-Martin (1995), or posit that customers' loyalty guarantees the leader cheaper distribution channels, as in Stein (1997) and Canton and Uhlig (1999). In this paper, I develop an explanation that differs from previous ones assuming that the leader has no cost advantage over outsiders. In addition, and perhaps more interestingly, in my model the persistence of leadership is beneficial to growth.

My results depend on two key assumptions. First, the leader has a move advantage in the next patent race. Second, innovations are incremental, i.e. non-drastic.[1] The first assumption is natural, since outsiders are likely to learn of the latest innovation only with some delay. The second assumption squares well with a stylized fact that emerges from many empirical studies, namely that incumbents are likely to dominate incremental innovations, while more radical technical changes tend to be associated with the entry of new firms (see Rosen, 1991, and Henderson, 1993).

The intuition behind persistence is as follows. Under free-entry by outsiders, the

[1] An innovation is drastic if the patentee is unconstrained by outside competition and can therefore engage in monopoly pricing.

zero-profit condition fully determines aggregate R&D investment. Taking aggregate R&D effort as given, the leader perceives that the expected timing of the next innovation is independent of his own R&D effort. In appraising the incentive to innovate he thus neglects current profit, just as outsiders do. This means that Arrow's replacement effect vanishes. Since the leader, unlike outsiders, can engage in monopoly pricing with no fear of being displaced, he will value the next innovation higher than outsiders. As a result, he has a greater incentive to innovate and will pre-empt outsiders (Gilbert and Newbery, 1982).

This reasoning produces an important collateral result: under persistent leadership, the value of being leader exceeds current monopoly profit, for the move advantage assures the leader of extra-profits in the subsequent patent races despite free entry by outsiders. This extra-profit positively affects the incentive to innovate. Thus in my model the persistence of monopoly leads to higher growth rates. By contrast, previous explanations of persistent leadership tend to predict a negative effect on growth. After presenting my results, I develop the comparison more fully.

The rest of the paper is organized as follows. In section 2, in a partial equilibrium setting I analyze the conditions leading to leapfrogging and to persistent monopoly. The insights of this section are then embedded in a simple general equilibrium model. Section 3 analyzes the case of leapfrogging, section 4 that of persistent leadership. Some extensions are analyzed in section 5. Section 6 discusses the relevant literature and offers some concluding remarks.

2. BACKGROUND

In this section I argue that persistent leadership is obtained when innovations are non-drastic and the leader has a move advantage in the R&D game. To underscore that the persistence result is independent of the details of the particular growth model that I develop below, the argument is cast in a partial equilibrium framework.

Consider two successive innovations. Figure 1 illustrates the product market equilibrium. To simplify, I have portrayed the case of cost-reducing innovations, but the argument is the same for quality improvements. The first innovation lowers the cost from c_0 to c_1, and the second lowers it further to c_2. Figure 1 assumes that both innovations are non-drastic, but a two-step lead allows monopoly pricing. However, the following analysis is more general.

The leader owns a patent covering the first innovation. His current profit is π (area c_0ABc_1 in Figure 1). If the second innovation is made by a firm other than the leader, under Bertrand competition the price falls from c_0 to c_1,[2] the incumbent's profit is driven to zero, and the new leader's profit is π^B (area c_1CEc_2). If, however, the second innovation is obtained by the leader, he applies monopoly pricing, p^M, and earns π^M (area p^MFGc_2). Clearly, $\pi^M \geq \pi^B$, and for non-drastic innovations the inequality is strict.

I now focus on the race for the second innovation. The timing of the innovation is stochastic and is described by a Poisson discovery process with hazard rate $h(n)$, where n is aggregate R&D investment and $h(.)$ is an increasing and weakly concave function with $h(0) = 0$. As in Segerstrom, Anant and Dinopoulos (1990), the concavity of $h(.)$ reflects the presence of external diseconomies in research. When the innovation occurs, the probability that firm i is granted the patent is n_i/n. There is free entry in the R&D sector.

With infinite patent life and no further innovation in prospect, the second innovation is worth π^B/r to an outsider, where r is the interest rate. Outsiders' instantaneous expected profit is $\frac{n_i}{n}h(n)\frac{\pi^B}{r} - n_i$, so that the zero-profit condition for outsiders is:

$$\frac{h(n)}{n}\frac{\pi^B}{r} = 1. \tag{1}$$

This condition completely determines aggregate R&D effort. This means that the

[2] It is assumed that the antitrust law prohibits collusion.

outsiders' aggregate best-response curve has slope -1.

Now consider the leader. Denote by n^O the outsiders' aggregate investment and by n^L the leader's effort. The value of being a leader, V^L, is determined by the following asset condition:

$$rV^L = \pi - h(n)V^L + \frac{n^L}{n}h(n)\frac{\pi^M}{r} - n^L \tag{2}$$

which says that each security issued by the leader pays the flow of monopoly profit π less the expected capital loss $h(n)V^L$ that will be incurred when current monopoly profit is terminated by the next innovation plus the expected capital gain that will occur if the leader wins the race, obtaining an innovation that is worth π^M/r to him, less R&D cost.

In a Stackelberg equilibrium, the leader perceives that n is given by (1), and therefore the last two terms in (2) reduce to $(\pi^M/\pi^B - 1)n^L \geq 0$. With non-drastic innovations, $\pi^M > \pi^B$ and V^L is strictly increasing in n^L: therefore the leader will do all the research. This is Gilbert and Newbery's pre-emption result. With drastic innovations, $\pi_M = \pi_B$ and V^L is independent of n^L. As a result, it is a matter of indifference whether research is conducted by the leader or by outsiders.

Consider next a simultaneous moves game. The outsiders' aggregate best-response function (1) does not change. The leader's best-response function is obtained by solving (2) for V^L and maximizing taking n^O rather than n as given. At $n^O = 0$, the leader's first order condition is:

$$h'(n)\frac{\pi^M - \pi}{r} - 1 - \frac{h(n) - nh'(n)}{r} = 0. \tag{3}$$

A simple argument from Arrow (1962) shows that $\pi^B > \pi^M - \pi$. Since $h(.)$ is weakly concave and $h(0) = 0$, one has $h'(n) \leq h(n)/n$, implying that when (1) holds the left-hand side of (3) is negative. This means that the leader's stand-alone incentive to innovate is less than outsiders', so that at equilibrium $n^O > 0$ must hold.

The foregoing argument, however, has not yet established that $n^L = 0$. The leader's incentive to innovate may be increasing in n^O because the replacement effect weakens as n^O increases. To determine whether the leader does any research at all, one must evaluate the first order condition at $n^L = 0$. This gives:

$$\left[\frac{h(n)}{n}\frac{\pi^M}{r} - 1\right][h(n) + r] - h'(n)\pi = 0. \tag{4}$$

When innovations are drastic, $\pi^M = \pi^B$ so when (1) holds the first term inside square brackets vanishes. This means that the left-hand side of (4) is negative and the leader does no research ($n^L = 0$). This gives us Reinganum's (1983) leapfrogging result. In general, however, one cannot exclude the possibility that when innovations are sufficiently small at equilibrium $n^L > 0$.

Table 1 summarizes our conclusions concerning who conducts the research (the aggregate R&D effort is always determined by the outsiders' zero-profit condition). So far, endogenous growth models have focused on the top-left cell of Table 1; here I focus on the bottom-right. However, the ideas of the paper may also apply to the bottom-left cell if innovations are small enough.[3]

[3] With an infinite sequence of innovations, the value of each patent is endogenously determined as a function of future R&D effort. This does not change the conditions that produce persistence of monopoly or leapfrogging, and makes it possible to extend the above arguments to the case of constant returns to scale in R&D. Indeed, when $h(n)/n$ is constant, equation (1) no longer determines n if the value of the innovation is exogenous. With sequential innovations, however, the value of the innovation depends on the duration of transitory monopoly; equation (1) would thus determine the R&D effort in the next patent race, which in a steady state must coincide with current R&D effort.

Table 1. Who conducts the research?

size of innovations	*timing of moves in the patent race*: simultaneous moves	the leader moves first
drastic	outsiders only (Reinganum)	indeterminate
nondrastic	outsiders and (possibly) the leader	leader only (Gilbert and Newbery)

3. LEAPFROGGING

I now embed the insights from the previous section in a simple growth model. I use a one-sector version of the model of Barro and Sala-i-Martin (1995, ch. 7), but the main results are more general and can be re-produced in many other models with quality improvements. In this section I focus on the case of simultaneous moves in the R&D game, assuming that the current leader does no research and is therefore systematically replaced (which is correct if innovations are quasi-drastic). Such a leapfrogging equilibrium is standard in the endogenous growth literature. I develop it in some detail in order to present my assumptions in a familiar setting and also to get a benchmark to contrast with the persistent-leadership equilibrium.

The economy is populated by identical individuals whose mass is normalized to 1. Each individual has linear intertemporal preferences: $u(c) = \int_0^\infty ce^{-rt}dt$, so that the rate of time preference r coincides with the equilibrium rate of interest. Each individual inelastically offers one unit of labor. The final good y is produced in a perfectly competitive market using labor (which is in fixed supply) and an intermediate good according to the following production function: $y_k = X_k^\alpha$, where $X_k = \sum_{s=0}^{k} q^s x_s$ is the quality-adjusted input of a composite good which combines all past generations of intermediate goods, and $0 < \alpha < 1$.

Technical progress takes the form of an increase in the quality of intermediate goods: $q > 1$ is the size of each innovation and k is the number of past innovations. The size of innovations is exogenous (this assumption will be relaxed in section 5). Since different generations of the intermediate good are perfect substitutes, it is clear that in equilibrium, only the best quality will be used, so that the production function reduces to $y_k = q^{k\alpha} x_k^{\alpha}$. Independently of its quality, the intermediate good is produced using the final good with a constant marginal rate of transformation that is normalized to 1. The final good may be consumed, used to produce intermediate goods, or used in research.

From the production function one obtains the demand for the latest generation of the intermediate good:

$$x_k = \alpha^{1/(1-\alpha)} q^{k\alpha/(1-\alpha)} p_k^{-1/(1-\alpha)}, \tag{5}$$

where p_k is its price. In a stationary equilibrium p_k will be constant, and from (5) it follows immediately that $y_{k+1}/y_k = q^{\alpha/(1-\alpha)}$. This is the growth factor between periods (a period is the random time interval between two innovations), and I denote it by $g \equiv q^{\alpha/(1-\alpha)}$. In a steady state, consumption, the input of intermediate goods, and R&D investment will all grow at rate g between periods.

The k-th innovator holds a patent covering the k-th intermediate good and will price it so as to maximize $\pi_k = (p_k - 1)x_k$. I distinguish two cases. When the leader through successive innovations has obtained such a lead that no competitor can profitably underprice him, or when innovations are drastic (i.e. $\alpha q \geq 1$), monopoly pricing applies. Since the elasticity of demand is $1/(1-\alpha)$, the monopoly price is $p^M = 1/\alpha$, the same in all periods. The corresponding monopoly profit is:

$$\pi_k^M = \alpha^{1/(1-\alpha)} \left(\frac{1}{\alpha} - 1\right) q^{k\alpha/(1-\alpha)}, \tag{6}$$

or $\pi_k^M = \pi^M g^k$ where $\pi^M \equiv \alpha^{\alpha/(1-\alpha)}(1-\alpha)$.

If, instead, innovations are non-drastic ($\alpha q < 1$) and the next best quality is available to a firm other than the current leader, the leader is constrained by outside competition. Assuming Bertrand competition among the potential producers of the intermediate goods, the outcome will be a limit-pricing equilibrium where the leader prices at $p^B = q$ and drives his competitors out of the market. The corresponding profit is:

$$\pi_k^B = \alpha^{1/(1-\alpha)} \left(q-1\right) q^{k\alpha/(1-\alpha)} q^{-1((1-\alpha)}, \tag{7}$$

or $\pi_k^B = \pi^B g^k$ where $\pi^B \equiv \alpha^{1/(1-\alpha)}(q-1)q^{-1((1-\alpha)}$. I assume that innovations are non-drastic, i.e. $\alpha q < 1$; this implies $p^B < p^M$ and $\pi^B < \pi^M$. [4]

The research sector is modeled as in section 2. Research can be conducted by the leader or by outsiders. There is free entry by outsiders. Let n_k denote R&D investment, in units of the consumption good, to obtain the $k+1$-th innovation. For simplicity, I specify the aggregate hazard function as $h(n) = \lambda_k n_k^{\beta}$, with $\beta \leq 1$. When $\beta = 1$ one re-obtains the standard case with constant returns in the R&D sector. When the innovation occurs, the probability of firm i being granted the patent is n_{ik}/n_k.

At equilibrium, outsiders' expected net profit must be equal to zero, i.e.:

$$\lambda_k n_k^{\beta-1} E(V_{k+1}) = 1, \tag{8}$$

where $E(V_{k+1})$ is the expected value of the $k+1$-th innovation. Positing that the leader will be displaced by an outsider in the next race, $E(V_{k+1})$ is determined by the following asset condition:

$$rE(V_{k+1}) = \pi_{k+1}^B - \lambda_{k+1} n_{k+1}^{\beta} E(V_{k+1}), \tag{9}$$

[4] The leapfrogging equilibrium that we find in this section can be immediately extended to the case of drastic innovations by simply replacing π^B with π^M.

which says that securities issued by the leader pay the flow profit π^B_{k+1} less the expected capital loss $\lambda_{k+1} n_k^\beta E(V_{k+1})$ that will be incurred when the next innovation is achieved (driving the leader's profit to zero). Equations (9) and (10) can be combined into:

$$\lambda_k n_k^{\beta-1} \frac{\pi^B_{k+1}}{r + \lambda_{k+1} n^\beta_{k+1}} = 1. \tag{10}$$

In order to guarantee the existence of a steady state with positive growth, following Barro and Sala-i-Martin (1995, p. 250) I assume that

$$\lambda_k = \lambda g^{-\beta k}. \tag{11}$$

Under this assumption, in a steady state the hazard rate $z_k \equiv \lambda_k n_k^\beta$ will be constant across periods. Equation (10) reduces to:

$$g \frac{\pi^B}{r + z} = \frac{z^{(1-\beta)/\beta}}{\lambda^{1/\beta}}. \tag{12}$$

Since the left-hand side of (12) is decreasing and the right-hand side is increasing in z, there is a unique steady state. Implicit differentiation shows that the steady-state level of research is a decreasing function of the rate of time preference r and an increasing function both of the productivity of R&D effort λ and the step size between innovations q.

4. PERSISTENT LEADERSHIP

In this section I assume that the current leader has a move advantage in the patent race starting after the latest innovation. The argument of section 2 then implies that there will be a pre-emption equilibrium in which all research is done by the leader. But the amount of research is still determined by the outsiders' zero-profit condition, as in the leapfrogging model. The key insight of this section is that in the pre-emption equilibrium the outsiders' incentive to innovate is greater than in the leapfrogging model.

To simplify matters, I focus on the case in which each single innovation is non-drastic but a two-step lead gives the leader monopoly pricing power, that is:

$$\alpha q^2 \geq 1 > \alpha q. \tag{13}$$

This assumption will be relaxed in the following section. Under assumption (13), if the current leader obtains the k-th innovation, he can charge the monopoly price p^M and earn π_k^M. If the innovation is obtained by an outsider, the equilibrium price will be p^B with associated profit π_k^B.

Denote the expected value of the k-th innovation to the current leader by $E(V_k^L)$. This is implicitly determined by the following arbitrage condition:

$$rE(V_k^L) = \pi_k^M - \lambda_k n_k^\beta E(V_k^L) + \lambda_k n_k^L n_k^{\beta-1} E(V_{k+1}^L) - n_k^L \tag{14}$$

which can be interpreted like equation (2) above. Comparing (14) with (10), note the added term $\left[\lambda_k n_k^{\beta-1} E(V_{k+1}^L) - 1\right] n_k^L$, which captures the extra-profit accruing to the winner of the k-th patent race in the subsequent races, in addition to the transitory profit π_k^M.[5]

The expected value of the k-th innovation to an outsider, $E(V_k^O)$, is given by:

$$rE(V_k^O) = \pi_k^B - \lambda_k n_k^\beta E(V_k^O) + \lambda_k n_k^L n_k^{\beta-1} E(V_{k+1}^L) - n_k^L. \tag{15}$$

The added term $\left[\lambda_k n_k^{\beta-1} E(V_{k+1}^L) - 1\right] n_k^L$ in (15) is the same as in (14). The reason is that a firm leading by three or more steps will get the same profit as a firm leading by only two steps, implying that the extra-value of being a leader is independent of the current cost advantage.

From (14) and (15) one obtains:

$$E(V_k^L) - E(V_k^O) = \frac{\pi_k^M - \pi_k^B}{r + z_k}. \tag{16}$$

[5] In the leapfrogging model, the term $\left[\lambda_k n_k^{\beta-1} E(V_{k+1}^L) - 1\right] n_k^L$ vanishes, because $n_k^L = 0$ and, from the outsiders' zero-profit condition, $\lambda_k n_k^{\beta-1} E(V_{k+1}^L) = 1$.

Since $\pi^M > \pi^B$, the leader has a greater incentive to innovate than any outsider: $E(V_k^L) > E(V_k^O)$. The effect on equilibrium is two-fold. First, it implies that in a Stackelberg equilibrium the leader conducts all the research (see section 2 above). Second, outsiders' incentive to innovate is greater than in the leapfrogging model.

To show this, let us focus on the steady state where $E(V_{k+1}^L)/E(V_k^L) = E(V_{k+1}^O)/E(V_k^O) = g$. Free entry to the R&D industry implies:

$$\lambda_k n_k^{\beta-1} E(V_{k+1}^O) = 1, \tag{17}$$

i.e., a zero profit condition for the outsiders. From (16) and (17) I get:[6]

$$E(V_k^L) = \frac{\pi_k^M - \pi_k^B}{r+z} + \frac{n_k}{gz}. \tag{18}$$

Now substitute (18) into (15) and recall that the leader does all of the research ($n_k^L = n_k$) to obtain:

$$E(V_k^O) = \frac{\pi_k^B}{r+z} + gz\frac{\pi_k^M - \pi_k^B}{(r+z)^2}. \tag{19}$$

The first term on the right-hand side of (19) is the same as in the leapfrogging model; the second term is the extra-value of being leader discussed above. Since $\pi_k^M > \pi_k^B$, $E(V_k^O)$ is greater than in the leapfrogging model. To summarize, the leader's incentive to innovate is greater than outsiders', and both are greater than in the leapfrogging model. [7]

Obviously, a greater incentive to innovate leads to faster growth. This can be seen by substituting (19) into (16), yielding:

$$g\left[\frac{\pi^B}{r+z} + gz\frac{\pi^M - \pi^B}{(r+z)^2}\right] = \frac{z^{(1-\beta)/\beta}}{\lambda^{1/\beta}}, \tag{20}$$

[6] Note from (14) that the following transversality condition must hold: $r - (g-1)z > 0$. If this condition is violated, consumers have an incentive to postpone consumption indefinitely.

[7] If innovations are drastic, $\pi_k^M = \pi_k^B$ and the second term in (19) vanishes. The outsiders' incentive to innovate would thus be the same as the leader's, and equal to the incentive to innovate in the leapfrogging model.

which implicitly defines the model's steady state. Tedious algebra shows that when assumption (13) holds, the term inside square brackets is decreasing in z, which implies that there is a unique steady state. Since the left-hand side of (20) is greater than that of (12), it follows immediately that the economy grows faster than in the leapfrogging model.[8]

To get an idea of the size of the positive effect of monopoly on growth, I have computed the average growth rate (which equals $z \log g$) for some representative parameter values. Setting $\alpha = 0.3, r = 0.06, \beta = 1, q = 2$, and $\lambda = 1$, I obtain an expected growth rate equal to 1.04% under persistent leadership and 0.87% under leapfrogging. For $\lambda = 2$, the growth rates are 4.16% and 3.53%, respectively. Clearly, the difference between growth rates may not be negligible.

Finally, consider expected social welfare. This is given by:

$$E(u) = \int_0^\infty e^{-rt} \left(\sum_{k=0}^{\infty} \Pr(k,t) c_k \right) dt, \tag{21}$$

where $\Pr(k,t) = e^{-zt} z^k t^k / k!$ is the probability that there will be exactly k innovations up to time t, and $c_k = y_k - x_k - n_k$ is consumption in period k. There are two conflicting effects of persistent leadership on social welfare. In each period k, consumption is greater in the leapfrogging model because net output $y_k - x_k$ is greater (due to $p^B < p^M$), and R&D investment is lower. However, the expected duration of each period is shorter under persistent leadership, so at any time t the expected value of index k will be higher. Either effect may prevail.[9]

[8] Qualitatively, the two models lead to similar comparative statics results: the steady state level of research is a decreasing function of the rate of time preference r and an increasing function both of the productivity of R&D effort λ and the step size between innovations q.

[9] Using the same parameter values as above, for $\lambda = 1$ expected social welfare turns out to be higher under leapfrogging ($E(u) = 6.978$) than under persistent leadership ($E(u) = 6.039$). However, for $\lambda = 2$, expected social welfare is $E(u) = 21.96$ under persistent leadership and $E(u) =$16.85 under

5. EXTENSIONS

In this section I analyze two extensions of the basic model. First, I relax simplifying assumption (13). Second, I show that my results carry over to endogenous innovation sizes.

Relaxing assumption (13), let us suppose that the incumbent needs an $(s+1)$-step lead to engage in monopoly pricing: that is, $\alpha q^{s+1} \geq 1 > \alpha q^{s}$. A firm that is leading by s steps will price at $p^{(s)} = q^{s}$, and get profit:

$$\pi_k^{(s)} = \alpha^{1/(1-\alpha)} \left(q^{s} - 1\right) q^{-s/(1-\alpha)} g^{k}, \tag{22}$$

while $p^{(s+\ell)} = p^{M}$ and $\pi_k^{(s+\ell)} = \pi_k^{M}$ for $\ell = 1, 2, \ldots$. The expected value of the k-th innovation to a firm that is leading by v steps is given by:

$$rE(V_k^{(v)}) = \pi_k^{(v+1)} - \lambda_k n_k^{\beta} E(V_k^{(v)}) + \lambda_k n_k^{(v)} n_k^{\beta-1} E(V_{k+1}^{(v+1)}) - n_k^{(v)}. \tag{23}$$

In order to solve the model, one needs to specify a boundary condition.[10] This is given by

$$E(V_k^{(s)}) = E(V_k^{(s+1)}) \tag{24}$$

which must hold because a firm leading by s steps would have monopoly pricing power if it got the next innovation, and the added term $[\lambda_k n_k^{\beta-1} E(V_{k+1}^{(s+1)}) - 1] n_k^{(s)}$ is also the same as for a firm leading by $(s+1)$ steps. Proceeding backwards, one can calculate $E(V_k^{(v)})$ for $v = s, s-1, \ldots, 0$. Given $E(V_k^{(0)}) = E(V_k^{O})$, one can then use the zero-profit condition for outsiders to determine the steady-state equilibrium. While

leapfrogging. It is no surprise that the leapfrogging equilibrium may outperform persistent leadership in welfare, since it is well known that the equilibrium rate of growth can exceed the socially optimal rate: faster growth, that is to say, is not necessarily socially beneficial.

[10] This cannot be done when $\alpha = 0$, i.e. the demand function for the intermediate good is unit-elastic, as in Grossman and Helpman (1991). In this case, there is no steady state with persistent leadership.

the algebra becomes quite messy indeed as s increases, the qualitative features of the basic model do not change.

I next show that the pre-emption equilibrium does not depend on the size of innovations being exogenously fixed. To do this in the most general way, consider again the partial equilibrium framework of section 2. Suppose that firms can choose not only the expected frequency but also the size of innovations (but that it is prohibitively costly to target drastic innovations). If a firm invests n_i in R&D and targets innovation q_i, its effective R&D investment is $n_i\gamma(q_i)$ where $\gamma(.)$ is a decreasing and concave function. Aggregate effective R&D investment is $n = \sum n_i\gamma(q_i)$, and the hazard function is $h(n)$. Firm i's probability of winning the race is $n_i\gamma(q_i)/n$.

Outsiders' instantaneous expected profit is now $n_i\gamma(q_i)\frac{h(n)}{n}\frac{\pi^B(q_i)}{r} - n_i$. The zero-profit condition requires that this expression must be non-positive for any choice of q_i. Clearly, all outsiders will target innovation q_i that maximizes $\gamma(q_i)\pi^B(q_i)$. Denote by $\hat{q}^O$ the optimal innovation size for outsiders. The zero-profit condition now becomes:

$$\frac{h(n)}{n}\frac{\gamma(\hat{q}^O)\pi^B(\hat{q}^O)}{r} = 1. \tag{25}$$

Again, this condition completely determines aggregate R&D effort.

Consider next the leader. The value of being a leader, V^L, is determined by condition (2) with π^M now depending on the size of the innovation: $\pi^M(q^L)$. In a Stackelberg equilibrium, the leader perceives that n is given by the free-entry condition (25) and therefore chooses n^L and q^L so as to maximize $\left[\gamma(q^L)\pi^M(q^L)/\gamma(\hat{q}^O)\pi^B(\hat{q}^O) - 1\right] n^L$. A revealed preference argument shows that the term inside square brackets is positive; therefore the leader will do all the research: $\gamma(q^L)n^L = n$. [11]

[11] The leader's target innovation size is determined so as to maximize $\gamma(q^L)\pi^M(q^L)$. Since monopoly output is lower than output under Bertrand competition, by the envelope theorem we get $d\pi^M/dq < d\pi^B/dq$ implying that the leader will target smaller innovations than outsiders: $\hat{q}^L < \hat{q}^O$.

6. CONCLUSION

In this paper, I have shown that the persistence of technological leadership may be explained by combining two reasonable assumptions: innovations are non-drastic, and the last innovator has a move advantage in the next race. I have also shown that under these assumptions, the growth rate will be higher than in a leapfrogging model. The welfare comparison of the two equilibria is ambiguous, however.

In general, endogenous growth models tend to predict that competition in the innovation sector is beneficial to growth: with monopoly in the research sector, the growth rate is lower than under free entry (see Barro and Sala-i-Martin, 1995). On the other hand, an increase in product market competition (e.g., a greater elasticity of demand for the intermediate good) reduces the incentive to innovate.[12] My model is broadly consistent with such predictions: persistent leadership allows the leader to engage in monopoly pricing, thereby increasing temporary profit, but does not eliminate competition in research. Thus, a framework in which monopoly persists but is continually under the threat of entry is more conducive to growth than either systematic leapfrogging or a monopoly with blockaded entry.

This conclusion, however, differs from those obtained by Barro and Sala-i-Martin, Stein, and Canton and Uhlig. Two modeling assumptions are responsible for this difference. First, the mark-up that a successful entrant can charge may depend on the duration of previous leadership (as in Stein and Canton and Uhlig) or it may not (as in Barro and Sala-i-Martin and the present model). Second, any advantage associated with leadership, be it a cost or a move advantage, may be passed over to the new leader (as in Stein, Canton and Uhlig, and the present model) or not (as in Barro and Sala-i-Martin).

To see how these different assumptions influence the effect of leadership persis-

[12] See, however, Aghion and Howitt (1998, ch. 7) for various attempts to reverse this conclusion.

tence on the growth rate, imagine that the leader's cost advantage increases with the duration of leadership: the longer the previous monopoly, the weaker any new entrant. This clearly implies that growth slows down as monopoly is entrenched,[13] but this effect is not at work in our model. On the other hand, consider Barro and Sala-i-Martin's implicit assumption that the cost advantage in research attaches to a particular firm (which in equilibrium will turn out to be the leader) and is not passed on to a new leader. This implies that the equilibrium rate of growth is the same as that predicted by the leapfrogging model, because even successful outsiders would never obtain any extra-profit. If the cost advantage was attached to leadership *per se*, the rate of growth would be higher under persistent leadership, as in my model.

Another noteworthy prediction of the persistent-leadership model is that the rate of entry and exit of new firms is uncorrelated with the rate of growth. However, it must be said that consistent leadership persistence is as unrealistic as systematic leapfrogging. Ideally, one would like to develop a theory in which incumbents hold sway for several periods but are eventually replaced by outsiders. It would also be desirable to link the entry of new firms to the size of innovations and to the business cycle, along the lines suggested by Cheng and Dinopoulos (1996) and Helpman and Trajtenberg (1994). While I have eschewed distracting assumptions here and focused on steady growth, I believe that the foregoing analysis of non-drastic innovations may help develop such a richer theory.

For instance, one could assume that the size of innovations is exogenous but stochastic: sometimes innovations are non-drastic, sometimes drastic. When they are non-drastic, the leader conducts all of the research, but when they are drastic, it is a matter of indifference whether research is conducted by the leader or by outsiders. In such a model, one would observe that all small innovations are obtained by the leader but some large innovations are obtained by outsiders, which fits the empirical

[13] However, an exogenous increase in the leader's cost advantage has ambiguous effects on growth.

evidence. The incentive to innovate would still be greater than in the leapfrogging model.

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