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CIDE

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R & D AND HUMAN CAPITAL: COMPETITION IN INNOVATION

Abstract

This paper develops a model of Cournot competition in innovation. This model introduces two new features. First, firm's investment in research and development is divided into two pieces, expenditures in human capital and expenditures in all other inputs (called R&D for simplicity). Second, the government also allocates resources to research and development, which affect the stock of knowledge available to the firms. Some interesting results arise from this model. First, investments in human capital and in R&D are increasing in the government's investment. Second, investments per firm are decreasing in the number of firms in the industry, but the totals are larger if some conditions on the elasticities are satisfied. Third, the welfare analysis tells us that if there are entry barriers, each firm is overinvesting in both inputs. On the other hand, if there is free entry, there are too many firms engaged in the innovative race.

Resumen

En este documento se construye un modelo de competencia en innovación tipo Cournot. Se introducen dos nuevas características. Primero, la inversión de las empresas en investigación y desarrollo es dividida en dos partes, gasto en capital humano y gasto en todos los otros insumos (nombrados I&D por simplicidad). Segundo, el gobierno también destina recursos a investigación y desarrollo, los cuales afectan el stock de conocimiento que está disponible para las empresas. Este modelo arroja algunos resultados interesantes. Primero, las inversiones en capital humano y en I&D son crecientes en la inversión del gobierno. Segundo, las inversiones de cada empresa son decrecientes en el número de empresas en la industria, pero las inversiones totales son mayores si se cumplen ciertas condiciones sobre las elasticidades. Tercero, el análisis de bienestar nos dice que si hay barreras a la entrada, cada empresa invierta más de lo óptimo en ambos insumos. Por otro lado, si hay libre entrada, hay demasiadas empresas participando en la carrera por innovación.

Introduction

There exists a very extensive literature that analyzes the problems of innovation. This literature points out different aspects associated to innovation. Some papers stress the role of market structure (Kamien and Schwartz, 1975; Loury, 1979; Tandon, 1984; Cohen and Levin, 1989). Some others, the role of patents (Griliches, 1984; Kortum and Lerner, 1997). There are papers that analyze the time-cost trade-off that arises in this set up (Lucas, 1971; Telser, 1982, 1987; Reinganum, 1989) and the private and social returns from the innovations (Mansfield, et. al. 1977). Others focus on the sources of invention and innovation (Jewkes, et. al., 1958; von Hippel, 1988). However, there are two important points that are not modeled in most of these studies.

First, in most of these papers there is no role for the human capital present in the firm.[1] There is no distinction between investment in human capital and investment in physical capital or in any other input. All the investment is grouped in research and development. However, it was long ago, when it was pointed out the important role played by human capital on the innovative process. For example, Maclaurin (1953) says: "We have now reached a state in many fields where inventions are almost made to order, and where there can be a definite correlation between the numbers of applied scientists employed (and the funds at their disposal) and the inventive results. But one really gifted inventor is likely to be more productive than half a dozen men of lesser stature." Or, as Schmookler (1966) argues: "Chance factors aside, the joint determinants of invention are (a) the wants which inventions satisfy, and (b) the intellectual ingredients of which they are made".

Since the important work on human capital by Schultz (1960) and Becker (1962), economists have applied it successfully in many fields. However, there is a lack of application on innovation.[2] This omission might be caused by the difficulties inherent to the analysis of product and process innovation. There exist two main difficulties. On the one hand, we know it is hard to devise a theoretical model of innovation because of the presence of uncertainty. A model of innovation must involve the analysis of something new and unknown. It also must take into account problems of asymmetric information since the producers of a new good have

[1] I should note, however, that in Telser (1982), past experience (previous knowledge) is implicitly taken into account since it gives a threshold to the firm over the costs that are going to be accepted. If the cost of production with the new technology resulting from the research outlay is lower that the previous cost, it is accepted; otherwise the firm keeps producing with the old technology.

[2] Without taking human capital into account, the outcomes of the innovative process are essentially lotteries, like "flipping coins" (see Barney (1997) for a nice example).

different information than the potential customers. Moreover, firms investing in R&D for product innovation face much greater market uncertainty than firms looking for a process innovation. On the other hand, it is very difficult to get objective measures of human capital and of the outcomes of innovation (Griliches, 1984, 1997; Wright, 1997). As is pointed out by Griliches (1997): "The major proximate sources of measured productivity growth in a sector are improvements in the quality of its labor force, improvements in the quality of inputs purchased from other industries, locally increasing returns to scale (at the enterprise level), and the contribution of public and private R&D in the form of better production and organizational techniques." Moreover, we usually know only the investments made by the successful firms. We are missing valuable information about all the other firms that were competing in the innovation of a given product.

However, there has recently arisen an interest in the study of the interaction of human capital, R&D, innovation, and technological change. These are the cases of Lucas (1988), Cohen and Levinthal (1989), Gill (1989), Malerba (1992), Eicher (1996), Kumar (1997), Nickell and Nicolitsas (1997), Zeng (1997).

Second, this literature has not taken into account the role of the government. The government also invests substantial resources in research and development. For example, the government invests money in basic research, which is then made available to everyone. These results then affect the behavior of the firms when making their private decisions. The government's investment affects the stock of knowledge that is available to all firms willing to invest in research and development.

In this paper, I set up a Cournot model of product innovation in which the innovation is successfully completed by one of N potential competitors engaged in an innovative race. Firms make investments in human capital and in other inputs (which I call R&D) in order to innovate and to introduce a new product into the market. The first firm, and only the first, that does so gets a reward. The government invests money in research and development in this industry (by giving grants to universities or by doing research by its own to produce basic knowledge which is made public).

In this model, we get some interesting results. First, the investments per firm in human capital and in R&D decrease as the number of firms in the industry increases. However, total industry investments are larger in a more competitive industry. Also, the expected time of introduction of the new product is shorter for more competitive industries even though the probability of introduction by any single firm decreases with competition. At this point we can say that society benefits from more competitive industries since it gets more new products over time. However, there are two sources of social loss in this set up. First, if we have an industry with a fixed number of firms, each firm overinvests in both human capital and R&D. Second, if there is free entry, there are too many firms competing in innovation to get the reward. Moreover, firms might not be fully exploiting the scale economies from their technology. There are another interesting results from this model. Private investments in human capital and in R&D are increasing in the government's investments. On the other hand, if, for whatever reason, the cost of human capital increases, we should see a decrease in the investment of both, human capital and R&D, under some conditions. However, it is also possible to see a decrease in the investment in human capital but an increase in the investment in R&D.

The structure of this paper is as follows. In the next Section I present an industry where the number of firms is fixed. Free entry is allowed in Section II. In Section III, we compare the outcomes of the previous Sections with the socially optimal outcomes. Conclusions are made in Section IV.

I. Industry with Entry Barriers

In this section, we analyze a model of product innovation in which the innovation is assumed to be made by the producer of the good. Also, we assume that the number of firms is fixed. An important point in this model is the date at which the innovation will be ready to be introduced into the market. That date is given by a probability distribution induced by the amount of money committed to R&D and the amount of human capital hired by the firm. This probability function is also affected by the investments in research and development made by the government. The first firm that comes up with the innovation gets a perpetual flow of rewards.[3] The firm that makes the innovation in first place is the only one that gets the perpetual reward; all the remaining firms make a loss given by the size of the committed investments in R&D and in human capital.[4] Thus, if there are two firms that make the same investments, only one of them gets the reward. However, this does not imply that the winning firm is "more efficient" than the other. It only was a luckier firm.

In this setting, an innovation is a new product that generates expected nonnegative profits to the firm that introduces it into the market.[5] However, *ex post* all firms except one end up having negative profits. An innovation should be

[3] It is implicitly assumed that the firm that makes the innovation keeps it secret. We do not allow all the other firms to copy the new product from the successful firm. Analogously, we can say that this firm gets a patent that lasts forever.

[4] This creates social losses because there will be a "duplication of efforts" in terms of R&D and in terms of human capital. This is always the case in this kind of models. The analogous to this problem is a horse race, where we want to know which is the fastest horse, but we want to have the fewest horses participating on the race (only the fastest one in the ideal case).

[5] This agrees with Tisdall and Federowicz (1994) who say: "The real test of an innovation is not its novelty or it cleverness, it is whether or not it adds or creates value for customers"

distinguished from an invention. When an invention is introduced commercially as a new or improved product or process, it becomes an innovation (Maclaurin, 1953).[6]

Think of an industry with N identical firms engaged in a game of innovation. Each firm, denoted by i, invests resources in R&D and in human capital. The present value of its investment in R&D is rx_i, where r is the cost of R&D (normalized to one) and x_i is the money allocated to R&D. The present value of its investment in human capital is wh_i, where w is the cost of human capital and h_i is the amount of human capital hired (number of scientific workers, for example. I am abstracting from any kind of moral hazard or adverse selection problems present at the time the firm hires these scientific workers). We assume that these costs are binding, so that at the end of the game every firm has committed x_i to R&D and wh_i to human capital. Moreover, these costs are assumed to be independent of any development that could occur in the future and are known to the firm at the beginning of the innovative race. That is, we do not allow firms to change their decisions when they get more information. With its investment, the i th firm buys a random variable, denoted by $\tau(x_i, h_i)$, induced by x_i and h_i that gives the uncertain date at which the project will be successfully completed. That is, it gives the uncertain date at which the innovation will be introduced into the market.[7] This random variable gives the *technological uncertainty* that the i th firm is facing in this setting. The environment faced by the i th firm is also affected by the government's investments in this industry. Let the government invest resources z to produce basic knowledge $f(z)$.[8] This knowledge affects the technology uncertainty faced by all the firms in the industry. Assume that $f(z)$ is strictly increasing and concave with $f(0) = 0$ and $\lim_{z \to \infty} f_z(z) = 0$. The very first firm that comes up with the innovation gets a constant perpetual flow of rewards V, which is assumed to be known by all the firms in the industry. Think of V resulting from the production of the new good in a monopolistic situation or from the sales of the technology rights to other firms (this is the case for some biotechnology firms, which discover a new drug and then sell the rights to some pharmaceutical firm).

[6] For example, the automobile was invented in the late nineteenth century. However, Henry Ford made both a product and a process innovation in this industry when he started the massive production of automobiles in the early twentieth century.

[7] I am assuming that when the innovation is done it is successfully introduced in the market. However, it is not the case in the real world where just two out of ten innovations are successfully introduced into the market and just 17% of the new products introduced into the market in 1991 were successful (Garud, Nayyar, and Shapira, 1997).

[8] The government is assumed to invest resources in basic research. The results then obtained are published and are public domain.

For simplicity, we assume that the distribution function governing the behavior of the uncertain date of introduction, $\tau(x_i, h_i)$, is given by the exponential function:

$$pr\{\tau(x_i, h_i) \leq t\} = 1 - e^{-f(z)g(x_i,h_i)t}$$

that is, $pr\{\tau(x_i, h_i) \leq t\}$ denotes the probability that firm i will introduce the innovation before certain date t.

For the exponential distribution function, we know that

$$E[\tau(x_i, h_i)] = \frac{1}{f(z)g(x_i, h_i)}$$

which gives the expected time of introduction of the innovation by the i th firm.

Now, we proceed to make some assumptions that will help us to solve this model.

Assumption 1. Firms' expectations are rational

The characteristics of the function $g(x,h)$, which will be important in our analysis, are stated below.

Assumption 2. $g(x,h)$ is twice continuously differentiable, strictly increasing, in both x and h, satisfying

- $g(0,h) = g(x,0) = 0 = \lim_{x\to\infty} g_x(x,h) = \lim_{h\to\infty} g_h(x,h)$ (1)
- there exist $\bar{x}$ and $\bar{h}$ (with $\bar{x}$ and $\bar{h}$ possibly zero) such that:
  - (i) $g(x,h) \geq xg_x(x,h) + hg_h(x,h)$ if $x \leq \bar{x}$ and $h \leq \bar{h}$
  - (ii) $g(x,h) < xg_x(x,h) + hg_h(x,h)$ if $x > \bar{x}$ and $h > \bar{h}$
- $g_{xh}(x,h) \geq 0$ or $g_{xh}(x,h) \leq 0$

From Assumption 1, all firms know the exact set up of the model. Moreover, they know the behavior of each other.

From Assumption 2 we have that while there may be an initial range of increasing returns to scale, they are eventually exhausted and we get into a region of diminishing returns to scale. The usefulness of this assumption will be clear later on when we study the case of an industry with free entry.

For the case in which $\bar{x}$ and $\bar{h}$ are different from zero, we define $(\bar{\bar{x}}, \bar{\bar{h}})$ as the solution to

$$\max_{x,h} \left\{ \frac{g(x,h)}{x + wh} \right\} \tag{2}$$

so that $\bar{x} = \bar{\bar{x}}$ and $\bar{h} = \bar{\bar{h}}$ if $\bar{x} = \bar{h} = 0$; but $\bar{\bar{x}} > \bar{x}$ and $\bar{\bar{h}} > \bar{h}$ if $\bar{x} > 0$ and $\bar{h} > 0$. The values $(\bar{\bar{x}}, \bar{\bar{h}})$ will be important in our discussion about the welfare properties of the equilibrium of this model.

From Assumption 1, firm i knows that any rival firm may introduce the innovation before it with a positive probability. To formalize this, let $\bar{\tau}_i$ be the random variable representing the unknown date at which any rival may be able to introduce the innovation. This random variable represents firm i's *market uncertainty*. Since firms' expectations are rational, we can express $\bar{\tau}_i$ as follows:

$$\bar{\tau}_i = \min_{1 \le j \ne i \le N} \{\tau(x_j, h_j)\}$$

This expression gives the unknown date at which the innovation will be introduced by any rival firm before firm i finishes its project.

Assumption 3. There are no private externalities in the innovative process so that the random variables $\tau(x_i, h_i)$ may be taken as independent.[9]

This Assumption makes our analysis closer to the property rights approach, which emphasizes the importance of patent protection. This is one extreme in this setting (the other is to assume that the innovation is a public good).[10] This is a very strong assumption in this model. However, it allows any firm to fully appropriate the returns from its investments, namely V, by introducing the new product before any other firm.

From Assumption 3 we have that the probability of the innovation being introduced by any firm, other than i, before certain date t is given by

$$pr\{\bar{\tau}_i \le t\} = 1 - e^{-f(z)a_i t}$$

where

$$a_i = \sum_{j \ne i} g(x_j, h_j)$$

is the degree of rivalry faced by the ith firm. The ith firm takes a_i as a constant. That is, we are assuming a Cournot competition, where each firm assumes that its actions will have no effect on the decisions of their rivals.

For any time $t \ge 0$, the ith firm will get the revenue flow V only if it is the first firm to come up with the innovation. This will happen if it is the case that

$$\tau(x_i; h_i) \le \min\{\bar{\tau}_i, t\}$$

[9] This is to say that there are no spillovers from the research of the firms. Also, it assumes there is no theft of secrets. All the knowledge is kept behind the walls of the innovating firm.

[10] We should note that we are using both assumptions in this model since the government's innovations are public while the firms' innovations are private.

Integrating the joint density of $(\tau(x_i,h_i),\bar{\tau}_i)$ over the relevant region, we have

$$pr\{\tau(x_i,h_i)\le \min\{\bar{\tau}_i,t\}\} = \frac{g(x_i,h_i)}{a_i+g(x_i,h_i)}[1-\exp\{-f(z)(g(x_i,h_i)+a_i)t\}]$$

Let ρ be the discount rate, assumed the same for all firms. By assuming that these firms are profit-maximizers, the i th firm chooses x_i and h_i, given a_i, z, w, ρ, and V to maximize its expected discounted profits. So, it solves the following problem:

$$\max_{x,h}\Pi(x,h;fa_i,z,w,\rho,V) = \max_{x,h}\left\{\frac{Vf(z)g(x,h)}{\rho(f(z)a_i+\rho+f(z)g(x,h))}-x-wh\right\} \tag{3}$$

If $\Pi(x,h;fa_i,z,w,\rho,V)\ge 0$ for some (x,h), then from Assumption 2, we know that a global maximum exists.

Assumption 4: $\Pi(x,h;fa_i,z,w,\rho,V)\ge 0$ for some x and h when $N=1$ (that is, in case of no rivalry, so that $a_i=0$).

This Assumption is just needed in order to get an interesting problem for the case in which there is just one firm in the industry. Otherwise, we would have no problem at all since this monopoly would not have any incentive to innovate.

If there is an interior solution, it must satisfy the following first-order conditions (where we omit the argument z for simplicity):

$$\frac{(fa_i+\rho)fg_x(x,h)}{[fa_i+\rho+fg(x;h)]^2}-\frac{\rho}{V}=0 \tag{4}$$

$$\frac{(fa_i+\rho)fg_h(x,h)}{[fa_i+\rho+fg(x;h)]^2}-\frac{w\rho}{V}=0 \tag{5}$$

The second-order conditions require the following matrix to be negative definite

$$|M| = \begin{vmatrix}(fa+\rho+fg)g_{xx}-2fg_x^2 & (fa+\rho+fg)g_{xh}-2fg_xg_h\\(fa+\rho+fg)g_{xh}-2fg_xg_h & (fa+\rho+fg)g_{hh}-2fg_h^2\end{vmatrix} \tag{6}$$

Equations (4) and (5) define implicitly $x^*=x^*(fa,z,w,\rho,V)$ and $h^*=h^*(fa,z,w,\rho,V)$. For a firm that assumes that the instantaneous probability of rival introduction is induced by a, x^* is the expected profit maximizing investment in R&D and h^* is the expected profit maximizing investment in human capital.

From this solution, we get the expected effects of ρ, V, and w on x^* and h^*. That is, investments in R&D, x^*, and in human capital, h^*, are decreasing in the discount rate, ρ. They are increasing in the reward, V. Finally, both investments are decreasing in the cost of human capital, w, if $g_{xh} \geq 0$ and $\frac{fa+\rho+fg}{2f} \geq \frac{g_x g_h}{g_{xh}}$. However, if $g_{xh} \leq 0$, then h^* is decreasing in its own cost but x^* is increasing in that cost.

An interesting result is the effect of the government investments on the firm's behavior. This result is stated in the following proposition.

Proposition 1: The private investments in human capital and in R&D are increasing in the government's investment in research and development.

Proof: From the first- and second-order conditions above, we get the following:

$$\frac{dx^*}{dz} = \frac{\rho(fg-\rho-fa)f_z}{(fa+\rho)f|M|} * \left\{ [(fa+\rho+fg)g_{hh} - 2fg_h^2]g_x + [2fg_x g_h - (fa+\rho+fg)g_{xh}]g_h \right\} \geq 0$$

$$\frac{dh^*}{dz} = \frac{\rho(fg-\rho-fa)f_z}{(fa+\rho)f|M|} * \left\{ [2fg_x g_h - (fa+\rho+fg)g_{xh}]g_x + [(fa+\rho+fg)g_{xx} - 2fg_x^2]g_h \right\} \geq 0$$

◆

Therefore, there is a positive effect from the increasing knowledge produced by the government's investment in basic research, which is available to all the firms in the industry. By having more knowledge available for free, all firms have a greater probability of making the innovation and, as a consequence, each single firm can make the innovation sooner. Thus, they have incentives to invest more resources in human capital and in R&D. That is, all firms are free loaders on the government's investment.

Now, we are interested in knowing how investments in R&D and in human capital are affected by the degree of rivalry. In order to do that, we need to impose some restriction on the function $g(x,h)$. This restriction will be used very often.

Assumption 5: The function $g(x,h)$ satisfies the following restriction whenever $g_{xh} \geq 0$

$$\frac{fa+\rho+fg}{2f} \geq \frac{g_x g_h}{g_{xh}} \tag{7}$$

Proposition 2:[11] Suppose Assumption 5 holds. Suppose $fa_i + \rho \geq fg$. Then investments in R&D, x^*, and investment in human capital, h^*, are decreasing in the degree of rivalry, a_i. However, if $fa_i + \rho < fg$ and/or Assumption 5 does not hold, anything can happen.

Proof: From the first- and second-order conditions above, we have the following:

$$\frac{dx^*}{da} = \frac{(fa+\rho-fg)f}{(fa+\rho)|M|}\left\{ [(fa+\rho+fg)g_{hh} - 2fg_h^2]g_x + [(fa+\rho+fg)g_{xh} - 2fg_x g_h]g_h \right\} \leq 0$$

$$\frac{dh^*}{da} = \frac{(fa+\rho-fg)f}{(fa+\rho)|M|}\left\{ [2fg_x g_h - (fa+\rho+fg)g_{xh}]g_x - [(fa+\rho+fg)g_{xx} - 2fg_x^2]g_h \right\} \leq 0$$

whenever $fa+\rho \geq fg$

♦

The response of the ith firm to changes in the degree of rivalry, a_i, depends on the expectations it holds about the sign of $fa+\rho-fg$. If this firm thinks that $fa+\rho \geq fg$ (that is, the increase in rivalry implies that the probability of introduction by any rival is bigger than the probability of introduction by firm i), then it decreases its investments in R&D and in human capital when there is an increase in the degree of rivalry. However, if this firm thinks that $fa+\rho < fg$ (and Assumption 5 still holds), then an increase in a_i induces this firm to increase its investments in R&D and human capital. Finally, if $fa+\rho < fg$ and Assumption 5 does not hold, anything is possible.

Now, we turn to the general equilibrium analysis. Given that the firms are identical, we have that $x_i = x^*$ and $h_i = h^*$ for all $i = 1,\dots,N$. Since firms' expectations are rational, we have that $a_i = a = (N-1)g(x^*,h^*)$. Thus, we have that $fa+\rho \geq fg$ for all $N \geq 2$. Therefore, from Proposition 2 we conclude that the investments in R&D and in human capital are always decreasing in the degree of rivalry, a_i.

Given the optimal value $a = (N-1)g(x^*,h^*)$, equations (4) and (5) define implicitly

[11] We should note that this is a partial equilibrium analysis because we still need to determine the optimal value of a_i.

$$x_N = x^*((N-1)f(z)g(x_N, h_N), z, w, \rho, V) \tag{8}$$

$$h_N = h^*((N-1)f(z)g(x_N, h_N), z, w, \rho, V) \tag{9}$$

Thus, x_N and h_N are the Cournot-Nash equilibrium levels of R&D and human capital, respectively, chosen by the firms. We should note that these optimal values depend on the number of firms in the industry.

Now, we want to know how the number of firms, N, affects this equilibrium.

Proposition 3: The optimal investments in R&D, x_N, and in human capital, h_N, are decreasing in the number of firms in the industry.

Proof:[12] By totally differentiating equations (8) and (9), we get

$$\frac{dx_N}{dN} = \frac{\frac{dx^*}{da}fg}{1-(N-1)f\left[\frac{dx^*}{da}g_x + \frac{dh^*}{da}g_h\right]} \leq 0$$

$$\frac{dh_N}{dN} = \frac{\frac{dh^*}{da}fg}{1-(N-1)f\left[\frac{dx^*}{da}g_x + \frac{dh^*}{da}g_h\right]} \leq 0$$

♦

Therefore, we expect to see lower investment per firm in research and development and in human capital in those industries where more firms are engaged in the innovative race. Hence, increasing competition reduces the investments in R&D and in human capital. That is, higher investments per firm are associated to higher concentration.

From Proposition 3 we get a reduction in investments per firm if there is an increase in the number of firms in the industry. This raises two interesting questions. First, what happens to the total investment in the industry? Second, what happens to the expected date of introduction of the innovation?

Let us analyze the first question. Define $X = Nx_N$ and $H = Nh_N$ as the total industry investments in R&D and in human capital, respectively.

Proposition 4: Suppose that $\frac{x_N}{N} \geq -\frac{dx_N}{dN}$ and $\frac{h_N}{N} \geq -\frac{dh_N}{dN}$ (that is, the elasticity is smaller than one). Then total industry investment in R&D, X, and total industry

[12] We are treating N as a continuous variable in this analysis.

investment in human capital, H, are increasing in the number of firms in the industry.

Proof: By totally differentiating X and H, we get

$$\frac{dX}{dN} = x_N + N\frac{dx_N}{dN} \geq 0$$

$$\frac{dH}{dN} = h_N + N\frac{dh_N}{dN} \geq 0$$

♦

Therefore, if the elasticities are smaller than one, we conclude that the total investments in R&D and in human capital are larger in industries with more firms than in more concentrated industries.

In order to answer the second question, we need to know the expected date at which the innovation will be ready to be introduced into the market. At this point it does not matter from the society's point of view which firm actually makes the innovation.

Let this random variable be defined as

$$\tau_N = \min_{1\leq i\leq N}\{\tau_i(x_N, h_N)\}$$

Thus, the probability of introduction of the new product into the market before certain date t, is given by

$$pr\{\tau_N \leq t\} = 1 - e^{-Nf(z)g(x_N,h_N)t}$$

Hence, in equilibrium, the expected date of introduction of the innovation is given by

$$E[\tau_N] = \frac{1}{Nf(z)g(x_N,h_N)}$$

Proposition 5: Suppose that the industry is in equilibrium. Suppose that $1 \geq -f\left\{\frac{dx^*}{da}g_x + \frac{dh^*}{da}g_h\right\}$. Then the expected date of introduction is a decreasing function of the number of firms.

Proof: In equilibrium, we have the following expression

$$\frac{d}{dN}\{Nfg(x_N,h_N) = fg\left\{\frac{1+f\left[\frac{dx^*}{da}g_x + \frac{dh^*}{da}g_h\right]}{1-(N-1)f\left[\frac{dx^*}{da}g_x + \frac{dh^*}{da}g_h\right]}\right\} \geq 0$$

Therefore, $\frac{d}{dN}E[\tau_N] \leq 0$

♦

Thus, suppose that marginal increases in investments in R&D and in human capital by any single firm induce the respective investments of all other firms to fall by a smaller amount. Then, from this Proposition we conclude that the expected date of introduction of the innovation is decreasing in the number of firms in the industry. Therefore, more competitive industries see the introduction of new products more often than more concentrated industries. However, if that assumption does not hold, it could be the case that the expected date of introduction of the innovation is increasing in the number of firms. It could be the case that the more competitive the industry, the less new products are introduced because the positive effect of an extra firm's investment is more than offset by the negative effect of the other firms' investments.

II. Industry with Free Entry

Now, assume that there is free entry in the industry. From (3), (4), and (5), we get the following expression for profits per firm:

$$\Pi = \frac{fa+\rho+fg}{2(fa+\rho)}\left(\frac{g}{g_x}+\frac{wg}{g_h}\right) - x - wh \tag{10}$$

Under these market conditions, we have the following results.

Proposition 6: If we are in the region of decreasing returns to scale (i.e., $\bar{x}=0$ and $\bar{h}=0$ or $x_N > \bar{x} > 0$ and $h_N > \bar{h} > 0$), then the expected present value of the profits is zero only in the limit; that is, $\lim_{N\to\infty}\Pi(x_N,h_N;fa,z,w,\rho,V)=0$ and $\Pi(x_N,h_N;fa,z,w,\rho,V)>0$ for all $N<\infty$.

Proof: In this case we are in the region where the function $g(x,h)$ is concave. Hence, from equation (10) we have that the expected profits are always positive but decreasing in the number of firms.

♦

The interesting case is when we get into the possible initial region of increasing returns to scale (i.e., when $0 < x_N < \bar{x}$ and $0 < h_N < \bar{h}$). The two possible outcomes under these conditions are stated in the following proposition.

Proposition 7: Suppose we are in the region of increasing returns to scale (i.e, $0 < x_N < \bar{x}$ and $0 < h_N < \bar{h}$). Then expected profits are decreasing in the number of firms in the industry and eventually they are exhausted. Suppose now that there exists $\overline{N}$ such that $\Pi_{\overline{N}}(.) = 0$. Then firms do not fully exploit the existing economies of scale present in this region.

Proof: Let the equilibrium profits be denoted by

$$\Pi_N = \Pi(x, h, fa)$$

where

$$a = (N-1)g(x,h)$$

and we omit z, ρ, w, and V to simplify notation.

Thus, in equilibrium we have that

$$\left.\frac{d\Pi_N}{dN}\right|_{\substack{x=x_N \\ h=h_N}} = \frac{d\Pi}{dfa}(N-1)fg_x\frac{dx_N}{dN} + \frac{d\Pi}{dfa}(N-1)fg_h\frac{d_N}{dN} + \frac{d\Pi}{dfa}fg + \frac{d\Pi}{dx}\frac{dx_N}{dN} + \frac{d\Pi}{dh}\frac{dh_N}{dN}$$

$$= \frac{d\Pi}{dfa}f\left\{(N-1)\left[g_x\frac{dx_N}{dN} + g_h\frac{dh_N}{dN}\right] + g\right\} + \frac{d\Pi}{dx}\frac{dx_N}{dN} + \frac{d\Pi}{dh}\frac{dh_N}{dN}$$

We know that $\frac{d\Pi}{dfa} = -\frac{(g_h + wg_x)fg^2}{2(fa+\rho)g_x g_h} < 0$.

On the other hand, since we are evaluating $\frac{d\Pi_N}{dN}$ at equilibrium, we have that $\left.\frac{d\Pi}{dx}\right|_{\substack{x=x_N \\ h=h_N}} = 0$ and $\left.\frac{d\Pi}{dh}\right|_{\substack{x=x_N \\ h=h_N}} = 0$.

Thus, we have that

$$sign\left(\frac{d\Pi_N}{dN}\right) = -sign(k)$$

where

$$k = (N-1)\left[g_x\frac{dx_N}{dN} + g_h\frac{dh_N}{dN}\right] + g \tag{11}$$

By substituting the expressions for $\frac{dx_N}{dN}$ and $\frac{dh_N}{dN}$ into equation (11), we get the following expression

$k =$

$$(N-1)\left\{ g_x \frac{\frac{dx^*}{da} fg}{1-(N-1)f\left[g_x \frac{dx^*}{da} + g_h \frac{dh^*}{da} \right]} + g_h \frac{\frac{dh^*}{da} fg}{1-(N-1)f\left[g_x \frac{dx^*}{da} + g_h \frac{dh^*}{da} \right]} \right\} +$$

g

$$= g\left\{ \frac{1}{1-(N-1)f\left[g_x \frac{dx^*}{da} + g_h \frac{dh^*}{da} \right]} \right\} > 0$$

Thus, $k > 0$. Therefore, $\frac{d\Pi_N}{dN} \leq 0$.

Now, suppose that $\Pi_N > 0$ for all $N < \infty$. Then from equation (8) and Proposition 3, we have that $\lim_{N\to\infty} x_N = 0$.

Also, from equation (9) and Proposition 3, we have that $\lim_{N\to\infty} h_N = 0$.

Since $g(0,0) = 0$, we conclude that $\lim_{N\to\infty} \Pi_N = 0$.

Now, suppose there exists $\overline{N} < \infty$ such that $\Pi_{\overline{N}} = 0$. Thus, from equations (3), (4), and (5) we have that

$$\Pi_N = \frac{fa+\rho+fg}{fa+\rho}\left(\frac{g}{g_x}\right) - x_{\overline{N}} - wh_{\overline{N}} = 0$$

$$\Pi_N = \frac{fa+\rho+fg}{fa+\rho}\left(\frac{wg}{g_h}\right) - x_{\overline{N}} - wh_{\overline{N}} = 0$$

Since $\frac{fa+\rho+fg}{fa+\rho} \geq 1$, we have that

$$\frac{g}{g_x} \leq x_{\overline{N}} + wh_{\overline{N}} \quad \text{and} \quad \frac{wg}{g_h} \leq x_{\overline{N}} + wh_{\overline{N}}$$

so that

$$\frac{g}{x_N + wh_N} \leq g_x \quad \text{and} \quad \frac{wg}{x_N + wh_N} \leq g_h$$

From problem (2), we know that $\frac{g}{\overline{\overline{x}}+w\overline{\overline{h}}} = g_x$ and $\frac{wg}{\overline{\overline{x}}+w\overline{\overline{h}}} = g_h$. Hence, $x_{\overline{N}} < \overline{\overline{x}}$ and $h_{\overline{N}} < \overline{\overline{h}}$. Therefore, firms are not fully exploiting the existing scale economies.

♦

From this Proposition it is clear that we need a region with increasing returns to scale for the function $g(x,h)$ if we want to get an equilibrium outcome which produces an industry structure with a finite number of firms.

Therefore, with free entry and increasing returns to scale we could get an equilibrium outcome in which there is a finite number of firms in the industry. But, in this industry structure, firms do not fully exploit the economies of scale in human capital and in R&D. However, if we get into the region of decreasing returns to scale, the result is that the profits are zero only in the limit. In this case, there would be an infinite number of firms with infinitely small investments in R&D and in human capital.

III. Welfare Analysis

We have two distortions in the private equilibrium of this model when we compared it with the socially optimal outcome. First, in the case of an industry with entry barriers, we have that firms are investing too much in R&D and in human capital. Second, in the case of an industry with free entry, we have too many firms engaged in the innovative race.

In the context of innovation, it is hard to argue whether the private returns are smaller, equal, or bigger than the social returns. The gap between the private and the social returns depends on three factors. First, the market structure of the innovator's industry. Second, whether the innovation is minor or major. Third, whether the innovation is a new product or a new process of production (Mansfield, et. al., 1977).

Moreover, we can find examples that go either way.[13] For these reasons, in what follows we assume that the private returns are equal to the social returns from an innovation. This assumption allows us to make comparisons between the private and the social outcomes.

The Industry with Entry Barriers

We know that in the Cournot-Nash symmetric equilibrium of Section I, the optimal value of a is determined by $a = (N-1)g(x,h)$.

[13] Examples where private returns are bigger than social returns are found in the following innovations: primary metals, door control, household-cleaning devices, dishwashing liquid. Examples where social returns are bigger than private returns are found in the following innovations: machine tool, construction material, paper (Mansfield, et. al., 1977). An extreme example in the latter case is the invention of Linear Programming by George B. Dantzig where the private returns are almost nothing compared to the social returns (I thank Professor Telser for suggesting this great example).

Given our assumption that the private and social returns coincide, the expected present value of the social (and private) returns in equilibrium is given by

$$V = V_P = V_S = N\Pi(x_N, h_N, (N-1)f(z)g(x_N, h_N))$$

However, when any single firm is maximizing its profits by choosing the optimal levels of investment in R&D and in human capital, it takes the value of a as given

Since firms take a as given, it is clear that they overinvest in R&D and in human capital. We show this in the next Proposition. Let x_N^* and h_N^* denote the socially optimal investments in R&D and human capital, respectively, for a fixed number of firms.

Proposition 8: Given a fixed number of firms in the industry, N ; in equilibrium, the investment in R&D and the investment in human capital per firm are higher than the socially optimal investments.

Proof: Let N be fixed. The socially optimal levels of investment, x_N^* and h_N^*, are the solution to the following problem

$$\max_{x,h}\left\{ N\Pi(x,h,(N-1)fg(x,h)) \right\}$$

Thus, x_N^* and h_N^* satisfy the following first-order conditions

$$\frac{d\Pi(x_N^*,h_N^*,(N-1)fg(x_N^*,h_N^*))}{dx}+\frac{d\Pi(x_N^*,h_N^*,(N-1)fg(x_N^*,h_N^*))}{dfa}(N-1)fg_x(x_N^*,h_N^*)$$
$=0$

$$\frac{d\Pi(x_N^*,h_N^*,(N-1)fg(x_N^*,h_N^*))}{dh}+\frac{d\Pi(x_N^*,h_N^*,(N-1)fg(x_N^*,h_N^*))}{dfa}(N-1)fg_h(x_N^*,h_N^*)$$
$=0$

On the other hand, the private equilibrium values, x_N and h_N, are given by

$$\frac{d\Pi(x_N,h_N,(N-1)fg(x_N,h_N))}{dx}=0$$

$$\frac{d\Pi(x_N^*,h_N^*,(N-1)fg(x_N^*,h_N^*))}{dh}=0$$

Recall that $\frac{d\Pi(.)}{dfa} = -\frac{(g_h + wg_x)fg^2}{2(fa+\rho)^2 g_x g_h} < 0$.

Hence

$$\frac{d\Pi(x_N^*,h_N^*,(N-1)fg(x_N^*,h_N^*))}{dx} > \frac{d\Pi(x_N,h_N,(N-1)fg(x_N,h_N))}{dx}$$

$$\frac{d\Pi(x_N^*,h_N^*,(N-1)fg(x_N^*,h_N^*))}{dh} > \frac{d\Pi(x_N,h_N,(N-1)fg(x_N,h_N))}{dh}$$

From the second-order conditions, we know that $\frac{d^2\Pi(.)}{dx^2} \leq 0$ and $\frac{d^2\Pi(.)}{dh^2} \leq 0$. Thus, $x_N^* < x_N$ and $h_N^* < h_N$.

◆

Since we know that $\lim_{N\to\infty} x_N = \lim_{N\to\infty} x_N^* = 0$ and $\lim_{N\to\infty} h_N = \lim_{N\to\infty} h_N^* = 0$, we have that in any market structure with a finite number of firms, all firms are overinvesting in both R&D and human capital. They coincide just in the limit. Therefore, the total industry investments in R&D and in human capital in the private equilibrium are bigger than the socially optimal ones, except perhaps in the limit. That is, $Nx_N > Nx_N^*$ and $Nh_N > Nh_N^*$ for all $N < \infty$; and $\lim_{N\to\infty} Nx_N \geq \lim_{N\to\infty} Nx_N^*$ and $\lim_{N\to\infty} Nh_N \geq \lim_{N\to\infty} Nh_N^*$.

The Industry with Free Entry

The socially optimal equilibrium is given by the solution to the following problem

$$\max_{x,h,N}\left\{ N\Pi(x,h,(N-1)fg(x,h)) \right\} \tag{12}$$

Denote by N^{SO} the number of firms, by x^{SO} the investment in R&D, and by h^{SO} the investment in human capital that solve this problem.

On the other hand, the free entry equilibrium number of firms, N^{FE}, is given by

$$\Pi(x^{FE},h^{FE},(N^{FE}-1)fg(x^{FE},h^{FE})) = 0$$

If it is the case that $N^{FE} < \infty$, then the net social benefit is zero. In this case, it could be the case that the configuration of the industry would not be optimal.

Proposition 9: If $\bar{x} > 0$ and $\bar{h} > 0$, then competitive entry induces too many firms to join the innovation race.

Proof: The first-order conditions for the socially optimal problem are the following

$$\frac{\left[N^{SO} fg(x^{SO},h^{SO})+\rho\right]^2}{Vf} = g_x(x^{SO},h^{SO})$$

$$\frac{\left[N^{SO} fg(x^{SO},h^{SO})+\rho\right]^2 w}{Vf} = g_h(x^{SO},h^{SO})$$

$$\frac{\left[N^{SO} fg(x^{SO},h^{SO})+\rho\right]^2}{Vf}=\frac{g(x^{SO},h^{SO})}{x+wh}$$

It is clear then that $x^{SO}=\bar{\bar{x}}$ and $h^{SO}=\bar{\bar{h}}$. By proposition 7, we have that $x_{N^{FE}}<\bar{x}$ and $h_{N^{FE}}<\bar{h}$. Proposition 8 implies that $x_{N^{SO}}>x$ and $h_{N^{SO}}>\bar{h}$. Moreover, proposition 3 asserts that $\frac{dx_N}{dN}<0$ and $\frac{dh_N}{dN}<0$. Thus, $N^{SO}<N^{FE}$.

♦

Therefore, the socially optimal outcome asks for a more concentrated industry. That is, there is too much competition in the innovative race in the free entry game.

IV. Conclusions

We have set up a model of product innovation. There are two new features in this model that have not been explicitly modeled in the literature. First, we break total investment in research and development in two pieces, human capital and all other inputs (which we call R&D). Second, we introduce the government into our set up. The government invests resources in research and development to produce basic research. Even though it is a simple model, we get interesting results. We conclude that the optimal investments in R&D and in human capital per firm are increasing in the reward available to the first firm that introduces the new product into the market. Also, both investments are inversely related to the discount rate. On the other hand, under certain conditions, the equilibrium investments in R&D and in human capital are decreasing with respect to the cost of human capital. However, if these conditions do not hold, human capital is decreasing in its cost but R&D is increasing in that cost. Finally, investments in human capital and in R&D are increasing in the government's investment in basic research.

Given that a certain stability condition is satisfied we are able to show that an increase in competition reduces the investments in R&D and in human capital per firm. However, total investments, in both research and development and human capital, are increasing in the number of firms in the industry. Even though the optimal investments can be decreasing in the number of firms, we show that the expected date of introduction of the new product is an increasing function of the number of firms in the industry.

If there is free entry in the industry, we get two results. First, if we get into the region of decreasing returns to scale, the only possible outcome is to get zero profits in the limit as $N\to\infty$. Second, if we are in the region of increasing returns to scale, it is possible to get an industry configuration with a finite number of firms and zero profits, but firms do not fully exploit these scale economies

Finally, we have two kinds of distortions compared to the socially optimal outcomes. On the one hand, if there are entry barriers, each firm is investing too much in both human capital and R&D. On the other hand, there are too many firms if we allow free entry.

There are some clear extensions of this model. First, we can introduce a technology for copying to allow the unsuccessful firms to copy the product from the successful firm. Second, we can make the reward variable over time to account for market changes. Third, we can try to make this model a dynamic one to account for the accumulation of human capital over time. With this set up, we can see whether or not successful firms have higher probability of being successful in the future.

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