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A B S T R A C T

Since the 1970's most industrialized countries have undertaken massive investment in computers and information technology (IT). Several stylized facts emerge from the empirical studies, see Landauer, 1993. In particular, they have found that this investment has not lead to a general increase in total factor productivity. This is known as the "productivity paradox". Also, some apparently inconsistent findings do emerge from these studies. In particular, the initial introduction of new IT by a firm tends to increase its market share, and finally, there is evidence that while in most industries productivity has failed to increase, in monopolistic and regulated industries there is evidence that computers and IT have increased productivity. We present a simple economic model of IT innovation. We find that in the model, measured productivity gains depends on market structure. In fact the "productivity paradox" is most likely to emerge in markets dominated by a small number of firms. It cannot emerge in either monopoly or highly competitive markets.

Keywords: Computers, Productivity, Slowdown, Strategic Investment.

1.- INTRODUCTION

Since the 1970's most industrialized countries have undertaken massive investment in computers and information technology. In the United States this investment has exceeded a trillion dollars. Several stylized facts emerge from both the empirical studies and firm surveys. In particular, they have found that this investment has not lead to a general increase in productivity. This phenomena has been called the "productivity paradox". However, some findings that seem inconsistent with the paradox also emerge from these studies. In particular, the introduction of computers tends to initially increase a firm's market share, and there is evidence that in monopolistic and regulated industries that computers have increased productivity.

How then can these stylized facts be reconciled? Several explanations of the productivity paradox have been proposed. One hypothesis is that businessmen have consistently overestimated the benefits of information technology, e.g. see Landauer (1993). However to economists, this seems implausible. As the amount invested has been huge over a period of 25 years, we would expect that if computers were truly unproductive, then the firms that did not introduce computers would be able to compete better than those that did. Hence, in competitive industries we should expect to eventually see smaller market shares for the firms that invested heavily in information technology, as entrants could adopt less computer intensive technology and compete with lower costs. As mentioned above the opposite is true, adoption of new IT is associated with increased market share and competitors tend to react by also adopting more IT. A second possibility, as presented by Leontief (1986), is that the productivity gains from computers may take a long time to be realized. The argument is that the productivity gains form the steam engine took 50 years to show up. However as Landuer argues this argument seems implausible because of the sheer magnitude of the investment in computers. Steam engines did not account for 10% of 18th century England's GDP. In the service sector, from 1976 to 1988 computers rose from 12% to 50% of investment. Given the size of this investment that will not payoff for 25 years, specially as the real interest rate was at record high level through the 1980's. Furthermore this hypothesis is not consistent with the differing rates of productivity gains across industries mentioned above.

Any attempt to reconcile the facts mentioned above is driven by some hypothesized market friction. The first hypothesis supposed that there is some bounded rationality, the second that there is a significant "learning by doing" externality that slows the widespread realization of benefits of computers.

In this paper, we propose an alternative hypothesis. That the friction comes from oligopolistic competition. That is, although the introduction of computers may be profitable for an individual firm, competition for market share may erode the productivity gains. Thus, computers may present an oligopoly with a prisoners dilemma problem. Although for each individual firm investment in computers may be profitable, collectively the industry would wish to halt their introduction. In particular when one firm innovates, the new technology allows it to increase its sales and its profits. If the other firms also adopt the new technology then the increased competition leads to an erosion of market share, and so the fixed cost of investing in computers is spread between a smaller number of sales. In the new equilibrium this later effect may dominate, and so for the industry, total factor productivity falls. We further show that this effect does not happen when there is a monopoly or when the market is competitive. Thus the intuition gained from the polar cases, that a profit maximizer would not do something unproductive, is misleading.

The model we present is the two stage model of strategic competition, see Shapiro [8] for a survey. In particular it is similar to the model of R&D investment developed in Brander and Spencer [2]. Recall that in this literature emphasis is on comparing the equilibrium level of investment with the socially efficient level. However, in this paper we are concerned with changes in the equilibrium when a discrete change in the technology, "computers" becomes available. Brander and Spencer [2] find that when competition is via a strategic substitute, firms would tend to over invest in

R&D, and so in equilibrium, total industry costs are not minimized for the equilibrium level of industry output. However, when the competitive variable is a strategic complement there is underinvestment in R&D, see Shapiro [8]. In contrast, we are able to show that investment in computers may be "unproductive" in both the strategic substitute, an the strategic complement case. At the start we wish to stress, that the purpose of this paper is to show the possibility of such and effect and so the model presented is very simple.

2.- THE QUANTITY SETTING MODEL

We will first consider the traditional Cournot model of oligopoly, see Shapiro [8] for a survey. There is a market with $N = \{1,2,\ldots,n\}$ firms who compete by choosing quantity of output q_i. Let a vector of the firm's output decisions be denoted by $q = (q_1,q_2,\ldots,q_n)$. Given the total production $Q = \sum_{i\in N} q_i$, the market inverse demand function determines a price $p = D(Q)$. Technology is of the following form, there is a fixed capital cost, ℓ, to produce the output and a variable cost, c, determined by the wage rate and the marginal product of labor. The initial production technology is the pair $T_o = (\ell_o,c_o)$. Given the output choice of each firm, the profits of firm i are $\pi_i(q,\ell_o,c_o) = D(Q)q_i - c_oq_i - \ell_o$.

We model an advance in computing or information technology as a new technique that requires a higher capital expenditure, but increases the marginal productivity of labor, lowering the marginal costs of production. The computer intensive technology is the pair $T_1 = (\ell_1,c_1)$, where $\ell_1 > \ell_o$ and $c_1 < c_o$. Although this model is extremely simplistic, we argue that it captures the salient features of the investment in computer and information technology. We are interested in what happens to total factor productivity, defined as $\dfrac{\Sigma_{i\in N}\, q_i}{\Sigma_{i\in N}(\ell_j+c_iq_i)}$, $j = 0,1$ after the introduction of computers intensive technology. As we are primarily interested in long run effects, our methodology is compare total factor productivity in the equilibrium when only T_o is available, with the equilibrium when firms can also choose between using T_o or T_1. Thus we abstract from any dynamics involved in the history of the market.

The extensive form game is as follows. At time zero a new technology, "computers" becomes available. The N firms each simultaneously chose to invest and adopt the new technology or remain with the old technology. The investment decisions are observable by all firms. At time 1 each firm chooses its period 1 level of production, fully informed about its competitors' investment decisions. We wish to study the subgame perfect equilibria of this game. That is, we require that whatever the profile of technologies adopted by the N firms, the market will reach the Nash equilibrium in the output market. Hence firms will "backward induct" and make their choices of technology based on the expected equilibrium payoffs. We will say that the "productivity paradox" holds, if in equilibrium all firms adopt the new information technology, T_1, and total factor productivity is lower than it would be at the equilibrium with only the old technology available.

We begin by showing that a monopolist will introduce a new technology if an only if it increases total factor productivity.

Let the initial technology be $T_o = (\ell_o, c_o)$ and suppose that at some date the new technology, $T_1 = (\ell_1, c_1)$, becomes available. Let q_1^* and q_2^* be the profit maximizing output levels for T_o and T_1 respectively. Let $\pi^*(\ell_o, c_o)$ and $\pi^*(\ell_1, c_1)$ be the maximum profits under T_o and T_1 respectively. A monopolist will introduce the new technology if and only if profits increase, that is $\pi^*(\ell_1, c_1) > \pi^*(\ell_o, \ell_o)$. Furthermore as $c_1 < c_o$ we have that $q_1^* > q_o^*$. Thus

$$p_1 q_1^* - c_1 q_1^* - \ell_1 > p_o q_o - c_o q_o^* - \ell_o > p_1 q_1^* - c_o q_1^* - \ell_o$$

and so

$$c_1 q_1^* + \ell_1 < c_o q_1^* + \ell_o$$

and so

$$c_1 + \frac{\ell_1}{q_1^*} < c_o + \frac{\ell_o}{q_1^*} < c_o + \frac{\ell_o}{q_1^*}.$$

Thus the new technology will be introduced if and only if average cost falls. As there is only one firm, average cost is the inverse of the total factor productivity index. Thus we may summarize with following proposition.

PROPOSITION 1.- *A monopolist will introduce the new technology, (computers), if and only if the new technology raises total factor productivity.*

We now discuss the case of an oligopoly.

We will assume that before T_1, there is a unique symmetric Nash equilibrium output, q^o. Profits for each firm will then be $D(nq^o)q^o - c_o q^o - f_o$. Suppose now that the new technology becomes available. When will a firm consider unilaterally introducing the computer intensive technology?. If the innovating firm's equilibrium profit in the subgame where it alone introduces the new technology is higher than the original equilibrium profit, then at least one firm should invest in computers. We show below that the profitability of the investment decision is not logically related to increasing productivity.

For simplicity we will use the *normalized linear* demand function $D(Q) = a - Q$. The Nash equilibrium output of each firm $q^o = \frac{a-c_o}{n+1}$ and equilibrium profits is $\pi_1^* = \left(\frac{a-c_o}{n+1}\right) - \ell_o$. If only one firm, say 1, chooses T_1, then elementary calculations show that in this subgame the equilibrium profit of firm 1 is, $\left(\frac{a+(n-1)c_D-nc_1}{n+1}\right) - \ell_1$. Let $\delta = \ell_1 - \ell_o$. Then a firm will innovate if and only if,

$$\left(\frac{a+(n-1)c_D-nc_1}{n+1}\right)^2 - \left(\frac{a-c_o}{n+1}\right)^2 > \delta \tag{1}$$

Suppose now that all firms innovate. Then, the equilibrium involves output of each firm is $q^1 = \frac{a-c_1}{n+1}$ and its equilibrium profits are $\left(\frac{a-c_1}{n+1}\right)^2 - \ell_1$. Thus there is a symmetric subgame perfect equilibrium where each firm invest in computers if,

$$\left(\frac{a-c_1}{n+1}\right)^2 - \left(\frac{a+(n-1)c_1-nc_o}{n+1}\right)^2 \geq \delta \tag{2}$$

If the equilibrium is symmetric, then as each firm has the same output and the same technology, the total factor productivity measure is the inverse of a firm's average cost. Comparing average costs for the industry before and after the innovation shows that a sufficient condition for productivity to fall is,

$$\delta > (c_o - c_1)\left(\frac{a-c_1}{n+1}\right) \tag{3}$$

If equation (1), (2) and (3) are compatible, then the innovation will be introduced by one firm, all firms will adopt it in equilibrium, and total productivity in the industry will fall.

We first show that (2) implies (1). That is, if there is an equilibrium where all firms adopt the new technology, then, it is profitable for at least one firm to adopt it. Thus the original technology cannot be used in a symmetric sub-game perfect equilibrium. Furthermore it can be shown that if equation (2) holds, then the symmetric equilibrium is the only subgame perfect equilibrium of the game. (A proof of this claim is provided in the appendix.)

Let $x = a-c_o$, $y = a-c_1$ and $z = c_o-c_1$. Then equation (1) can be written as $(x+nz)^2 - x^2 \geq \delta(n+1)^2$, and equation (2) can be written as $y^2 - (y-nz)^2 \geq \delta(n+1)^2$.

Suppose to the contrary that (2) holds and (1) does not, then we have that,

$$y^2 - (y-nz)^2 \geq \delta(n+1)^2 > (x+nz)^2 - x^2$$

or

$$-n^2z^2 + 2zny > n^2z^2 + 2xnz$$

Dividing by nz and substituting in the original terms yields,

$$c_o - c_1 \geq n(c_o - c_1)$$

a contradiction as $c_o > c_1$ and $n \geq 2$.

Thus when (2) holds there is a subgame perfect equilibrium that involves all firms adopting the new technology. Similar reasoning shows that it is the unique subgame perfect equilibrium. Therefore if (2) and (3) hold, or if the interval defined by,

$$\left[\left(\frac{a-c_1}{n+1}\right)^2 - \left(\frac{a+(n-1)c_1-nc_o}{n+1}\right)^2,\ (c_o-c_1)\left(\frac{a-c_1}{n+1}\right)\right] \tag{4}$$

is non-empty, and δ lies in this interval, then, in the new equilibrium all firms adopt the new technology and industry productivity falls.

Again substituting z and y, equation (3) becomes $\delta > z(y/n+1)$. Thus in order for (2) and (3) to hold it must be that

$$y^2 - (y-nz)^2 \geq (n+1)zy$$

or

$$-n^2z^2 - 2nyz \geq (n+1)zy$$

which yields the condition,

$$(n-1)(a-c_1) - n^2(c_o-c_1) \geq 0. \tag{5}$$

or equivalently,

$$\frac{a-c_1}{c_o-c_1} \geq \frac{n^2}{n-1} \tag{6}$$

When equation (5) holds, then the interval (4) is non empty and so it is possible to find a level of δ such that in the new equilibrium, all firms adopt the new technology, and productivity falls. Thus, we have established the following proposition.

PROPOSITION 2.- *When the demand curve is normalized linear, and when* $\frac{a-c_1}{c_o-c_1} \geq \frac{n^2}{n-1}$, *then the interval (4) is not empty, and so for some values of* δ *the productivity paradox will occur.*

It is informative to graph the equation $\frac{n^2}{n-1}$. The function is convex with a minimum at n = 2 and strictly increasing for n > 2. Fixing the market demand function and the size of the marginal productivity gain, by equation (6), whenever the value of the ration $\frac{a-c_1}{c_o-c_1}$ is greater than 4, then there is an interval of number of firms and a level of fixed costs such that the productivity paradox will emerge.

The equation (6) shows that the paradox cannot emerge for n = 1, or a monopoly. Furthermore, for given a value of the ratio $\frac{a-c_1}{c_o-c_1}$, there is a number of firms n' such that if n is greater than n', then the interval (4) is empty, and the paradox cannot emerge. Thus, if we take the perfect competitive market to mean one with a large number of firms, in this model we have the result that the productivity paradox is less likely the more competitive the market. Therefore, the intuition that a profit maximizing firm will not introduce an unproductive technology, gained from looking at either the monopoly or the competitive case where there is no (or little) strategic interaction, can be misleading when strategic issues are important.

The results of this section are not peculiar to the specification the demand function. Indeed if we were to consider the class of unit elastic demand functions p = A/Q, then the equivalent of condition (6), the sufficient condition for the paradox to occur, is that $c_o > (n-1)c_1$. Note that by definition this is always true for n = 2. Thus, in any duopoly with a unit elasticity demand function there is always a type of new information technology, T_1, such that, in the unique subgame perfect equilibrium both firms invest in computers and total factor productivity falls.

3.- THE PRICE SETTING MODEL

In this section we show that the results obtained previously are not dependent on the choice of output as the strategic variable. This is in contrast to the model where investment is a continuous variable, see Shapiro (8). In this case, when firms compete in quantities, then, in equilibrium, there is an overinvestment in R&D. However, if firms compete in prices, then, in equilibrium, firms underspend on R&D. In this section we show that overinvestment in computers can occur even when firms compete in prices. Thus, the effect of computers on productivity does not depend on the choice of strategic variable.

For simplicity we assume that there are two firms selling differentiated products. The firms compete in prices. Let the demand function for firm i be,

$$x_i = a - bp_i + p_j, \quad i \neq j, \quad i,j = 1,2$$

Technology and hence costs are as modeled in section 2. In the Nash equilibrium prices are,

$$p_i = \frac{(2ab + 2b^2c_i + a + bc_j)}{(4b^2 - 1)}$$

It is easy to see from the above equation, that if one firm unilaterally introduces the new technology, as its marginal cost is lower, then it will increase its market share. Profits in the Nash equilibrium are,

$$\pi_i = b\left(\frac{(a + 2ab + (1-2b^2)c_i + bc_j)}{(4b^2 - 1)}\right)^2$$

The condition that the new technology be adpted in equilibrium is

$$\pi_1 = b\left(\frac{(a + 2ab + (1+b-2b^2)c_1)}{(4b^2 - 1)}\right)^2 - \delta \geq b\left(\frac{(a + 2ab + (1-2b^2)c_o + bc_1)}{(4b^2 - 1)}\right)^2 \tag{7}$$

Productivity falling is equivalent to

$$\delta > \frac{by}{4b^2-1}\, z \tag{8}$$

where $z = 2ab - a + c_1(1+b-2b^2)$ and $y = c_o - c_1$.

Thus we have that equations (7) and (8) are consistent if,

$$\frac{bz^2}{(4b^2-1)^2} - b\left[\frac{z+y(1-2b^2)}{4b^2-1}\right]^2 > \delta > \frac{byz}{4b^2-1} \tag{9}$$

which implies that the productivity paradox will hold if

$$c_o(2b^2-1) > a(1+2b) + bc_1. \tag{10}$$

PROPOSITION 3.- *In the price setting model when (10) above holds, the productivity paradox may occur for some values of δ.*

4.- DISCUSSION

We have attempted to explain the stylized facts about the introduction of computing and information technology over last 25 years. The stylized facts are: that the investment in computers has been massive. However, it does not seem to have increased total factor productivity. The initial introduction of computers is associated with an increase in market share. However, in monopoly markets the introduction of computers and information technology seems to have raised productivity. To illustrate these findings, it is instructive to compare the U.S. banking industry, where regional markets are dominated by a small number of firms, and the telecommunications industry which, before 1984, was dominated by ATT. In both industries there was massive investment in information technology, notably ATM machines in banking and digital switching in telecommunications. In the banking industry, Citibank, the first firm to introduce ATM technology saw a large increase in its market share, see Landauer, (6). However in the long run, when all other firms introduced ATM machines, there appears to be no gains in productivity to the industry, Franke (3). In fact Strassmann (8), has found a (weak) negative correlation between intensity of IT usage and return on assets in the banking industry. In the telecommunications industry the experience has been the opposite, the conclusion of Gordon et al (4), is that the returns to R&D, embodied in new switching technology were very large, and probably increasing over time.

We argue that a simple oligopoly model is consistent with these stylized facts. We model the market as a two stage game where firms first decide what technology to adopt, and then compete either in quantities or prices. We compare productivity in the equilibrium of this game with productivity in the equilibrium of the game with only the old technology. In both the quantity and price competition model, we provide sufficient conditions for the productivity paradox to emerge. In the case of quantitiy competition, there is an interval of the number of firms in the industry when the condition could be met. In the price setting case, the condition for the paradox to occur depends on the relative slope of the demand function with respect to its own price. When this number is sufficiently high, the paradox might occur. Thus the paradox is most likely to emerge in markets with a small number of firms. It cannot arise in either monopoly or in markets with a large number of firms. Furthermore, we demostrated that in both models, introduction of the new technology implies an increase in market share. Thus, a simple model of oligopolistic competition seems to explain not just the productivity paradox, but is also consistent with the other stylized facts concerning the adoption of computers and information technology.

APPENDIX

Here we show that if equation (2) holds, then in the quantity setting model, the symmetric equilibrium described in the paper is the unique subgame perfect equilibrium (SPNE).

Suppose that there is a SPNE in which $m < n$ firms adopt the new technology, and $n-m$ do not. Then, by definition of an equilibrium, it must be that,

$$(a - nc_1 + c_i)^2 - (a - nc_o + c_i)^2 \geq d,$$

and

$$(a - nc_1 + c'_i)^2 - (a - nc_o + c'_i)^2 \geq -d,$$

where $c_i = (m-1)c_1 + (n - m)c_o$ and $c'_i = mc_1 + (n - m - 1)c_o$ and $d = \delta(n + 1)^2$. Manipulation of the above conditions and substituting x and z from the text, yields

$$(n - 2m)z(zn - zy) \geq d \geq (n - 2m)z(zn - 2x)$$

A necessary and sufficient condition for the above inequality to hold, is that $n \geq 2m$. However when a symmetric SPNE exists we have that

$$-n^2z^2 + 2ynz \geq d,$$

which combined with the above, and as by definition $y > z$, leads to

$$mn + n - n^2 > 0$$

But as $n \geq 2m$ the above implies that $2 > n$, a contradiction.

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