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ABSTRACT

A perfect–foresight model of entry and exit for an industry is developed. Early entry has the advantage of higher revenues per unit of output as the price is higher early on. Late entry has the benefits of learning from the experience of earlier entrants, and hence lower productions costs. These advantages are balanced off in a continuous time perfect foresight equilibrium. Exit takes place because the operation of high–cost, early–vintage technologies becomes unprofitable. The model generates S–shaped diffusion –– a well documented phenomenon in a wide variety of industries –– as well as staggered entry and exit, in a deterministic context. Examples are explicitly solved.

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1. Introduction

There is ample empirical evidence to support the view that the S-shaped diffusion path of an innovation is not an isolated phenomenon. In many cases, whether it is a process or a product innovation, plotting the usage/ownership of the new technology or the number of producers of the new product against time yields an S-shaped curve, as documented by, among others, Griliches (1957), Davies (1979), and Gort and Klepper (1982). This empirical recurrence can, by now, be viewed as a "stylized fact".

One class of non-strategic models of the adoption or entry decision, derives an S-shaped diffusion path as the outcome of the assumed heterogeneity across potential adopters, which however, is specified arbitrarily. These "probit type" models identify firm size, entrepreneurial attitudes, and the vintage distribution of capital as relevant sources of heterogeneity in the adoption decision. Other non-strategic models generating S-shaped diffusion paths are the so called "epidemic" models in which information about the new technology is spread by personal contact between users and non-users. The speed of diffusion is related to the frequency of interpersonal contact, which again, is specified exogenously.

Game-theoretic models of adoption, on the other hand, treat adopters as homogeneous and concentrate instead on the question of existence of the diffusion process itself, rather than on its specific properties, i.e. their S-shape (See Stoneman (1985) for a survey of the strategic and non-strategic models in the literature).

We show that S-shaped diffusion arises naturally in an environment in which homogeneous agents face the prospect of learning by doing, a la

Arrow (1962). We denote the act of adopting a new technology and/or beginning production of a new product by <u>entry</u>, while that of ceasing production as <u>exit</u>. In our model potential adopters (producers) are identical, of measure zero, and have perfect foresight. They incur a fixed cost at the moment of entry, and have variable costs of production that are vintage-specific. It is assumed that, due to learning by doing, costs decrease as entrants accumulate. However, these reductions in costs are not appropriated by the incumbent firms but spill over to potential entrants. Since the price of output also decreases, delaying entry entails both benefits and costs. Once a firm enters, it will continue production as long as the product price is above its marginal cost. Since the latter is constant (vintage-specific), exit will occur if the product price decreases sufficiently. Equilibrium is a diffusion path along which entrants earn zero discounted net profits, and are indifferent as to the date of entry.

We show that the equilibrium diffusion path approaches an endogenously determined size of total entrants, implying that, eventually, concavity sets in. More important, the initial convex region is tied to the rate at which the benefits from learning by doing decrease. In order to observe initial convexity of the diffusion path, it is sufficient (but not necessary) that the benefits from learning by doing decrease fast enough. Moreover, an exact S-shape is derived when learning by doing is isoelastic, as assumed by Arrow (1962).

In equilibrium, entry is proportional to the current flow of profits, a relationship similar to the one specified exogenously by Brock (1972). The exit rate is, in equilibrium, a fraction of the entry rate, so that net entry is always non-negative.

Learning by doing is the driving force of the model. But is it justifiable? Many instances have been reported where learning by doing has significant effects on cost reduction (See Alchian (1963), Sahal (1981), and Zimmerman (1982)). If such learning cannot be fully appropriated by the producers, costs will be lower as the number of producers grows. Evidence suggests that such spillovers are extensive in many industries (See Boston Consulting Group (1978) and Lieberman (1982)). Other circumstances under which this pattern of cost reduction can arise are when network externalities are significant, or when increasing returns in the industry supplying, say, equipment are present. A good example of all the above points is the recent dramatic reduction in the costs of getting computerized.

Not surprisingly, spillovers cause entry to proceed too slowly in equilibrium. A similar conclusion on the equilibrium amount of investment was reached by Arrow (1962). What is surprising, though, is that the total entry and exit coincide with their socially optimal magnitudes.

The next section presents the model and its results, followed by two examples. The welfare analysis is conducted in section 3. Conclusions close the paper.

2. The Model

Following Arrow, we assume (a) that learning is a function of cumulative gross investment (cumulative production of capital goods), and (b) that the technical changes that result from this learning are completely embodied in new capital goods. "At any moment of new time, the new capital goods incorporate all the knowledge then available, but once built, their productive efficiency cannot be altered by subsequent learning."[1]

We measure cumulative gross investment by n_t, the number of machines installed before time t. Each machine has a fixed installation cost $k(n_t)$, and a variable per-unit cost of production, $c(n_t)$. In spirit with Arrow's statement, we assume that $c' < 0$ and $k' < 0$. Moreover, once installed, the machines do not improve in their efficiency; that is, the cost structure of a machine is fully vintage-specific. A capacity constraint, normalized at unity, is assumed on each machine. Once installed, the machine does not depreciate. In the model, the number of machines per firm is arbitrary;[2] we henceforth assume one machine per firm.

Exit. Not all machines will be used forever. As entry proceeds, and as the product-price declines, it may be profitable to withdraw from production some early, high-cost vintages. Assume that p_t is non-increasing. Then, a machine is withdrawn as soon as p_t is equal to its marginal cost. Thus, vintage τ is withdrawn as soon at $p_t = c(n_\tau)$. Letting x_t denote cumulative exit up to time t, then

$$(1) \qquad x_t = c^{-1}(\min[p_t, c(0)]) = x(p_t).$$

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1 Arrow (1962), p. 157.

2 This arbitrariness will be recognized when we discuss the empirical implications of this model.

The function $x(p)$ is drawn in Figure 1.

Figure 1

Market Clearing. The market must clear at each instant at p_t. Industry supply at t is $n_t - x_t$. We assume a stationary demand function $D(p)$. Then $p_t = P(n_t)$, where $P(n)$ is the solution for p to the equation:

$$(2) \qquad n - x(p) = D(p).$$

Thus $P(n_t)$ is the price that must prevail following the entry of exactly n_t firms. Since x and D are both decreasing in p, $P(\cdot)$ is uniquely defined for all n.

Equilibrium. Firms are of measure zero, and thus take the time-path of prices as given. Time is continuous. If each entrant (a) earns zero discounted profits, and (b) is indifferent as to the date that he enters, the following condition must hold:

$$(3) \qquad \int_{\tau}^{\infty} e^{-r(s-\tau)}\max\{0,[P(n_s) - c(n_\tau)]\}ds - k(n_\tau) = 0$$

for all vintages $\tau \geq 0$. A <u>perfect foresight equilibrium</u> is a trajectory n_t which in non negative and non-decreasing, for which eq. (3) holds for all $\tau \geq 0$.[3] This definition of equilibrium takes into account optimal exit, because $P(\cdot)$ satisfies (2). This equilibrium does not specify <u>which</u> firm enters <u>when</u>, only their rate of entry.

<u>Proposition 1</u>: If an equilibrium trajectory n_t exists, it must be continuous.

<u>Proof</u>: Suppose that at some $t \geq 0$, n_t jumps by an amount Δ. The discounted revenue starting at $t+\epsilon$ is $\int_{t+\epsilon}^{\infty} e^{-r(s-t)}P(n_s)ds$, and as $\epsilon \to 0$, it converges to $\int_{t}^{\infty} e^{-r(s-t)}P(n_s)ds$. The cost of entry, on the other hand, converges to $k[n_t+\Delta]$, and the variable cost to $c(n_t+\Delta)$. Since both $k(\cdot)$ and $c(\cdot)$ are decreasing, if (1) holds at t, it must become positive at $t+\epsilon$ for some ϵ sufficiently small. Q.E.D.

Assuming that there are no firms in the industry to begin with, a corollary is that $n_0 = 0$, because there can be no mass point of entrants at time zero.

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[3] A more comprehensive definition would allow for the left-hand side of (3) to be negative for certain dates τ at which no entry would take place. Since demand is stationary, however, this can easily be ruled out.

The lifetime of each vintage of firms. The exit time of vintage τ firms is

$$(4) \qquad T_\tau = \begin{cases} \infty & \text{if } P(n_t) > c(n_\tau) \text{ for all } t \geq \tau, \\ \text{sol'n for T to } P(n_T) = k(n_\tau) & \text{otherwise} \end{cases}$$

Some firms live forever, since p_t is always above their variable costs. The lifetime of vintage τ is then $L_\tau \equiv T_\tau - \tau$.

Proposition 2: If the demand-curve has an intercept (i.e., $D^{-1}(0) < \infty$), then n_t is differentiable, and

$$(5) \qquad \dot{n} = \frac{P(n) - c(n) - rk(n)}{-\{k'(n) + r^{-1}c'(n)[1-e^{-rL_\tau}]\}}$$

Proof: The first term in (3) is differentiable with respect to τ because $P(\cdot)$ is bounded. Differentation of (3) with respect to τ and some rearrangement leads to (5). Q.E.D.

Proposition 1 tells us that $n_0 = 0$, while proposition 2 says that the equilibrium time-path of entry, $\dot{n}$, satisfies the differential equation (5). Since exactly one solution (n_t) exists to the equation, we have arrived at

Proposition 3: A unique equilibrium exists.[4]

Remark: Eq. (5) reveals the tradeoff involved in the equilibrium. Higher instantaneous profits (which are in the numerator) will speed up entry, whereas a higher reward to waiting in the forms of a larger decline in the present value of lifetime costs (in the denominator) will slow it down.

If learning by doing were identically zero for all n, (i.e., $k' = c' = 0$), there would be no learning by doing, and the only equilibrium would be one in which all entry was immediate at time zero.

The exit rate $\dot{x}$. From eq. (1), $\dot{x} = x'P'\dot{n}$. Differentiating in (2) yields $P' = 1/(D'+x')$, so that

$$\dot{x} = \frac{x'}{D'+x'}\dot{n} < \dot{n}$$

From Figure (1), $x' = 0$ when P is above $c(0)$, i.e., when n is small, so that $\dot{x} = 0$ early on. No exit takes place for a while. Moreover, net entry is always positive:

$$\dot{n} - \dot{x} = \frac{D'}{D'+x'}\dot{n} > 0.$$

so that the number of firms (and industry output), $n - x = n - x[P(n)]$,

[4] The solution is unique within the class of non-increasing p_t trajectories to which we confined our attention at the outset.

grows as long as $\dot{n} > 0$.[5]

Total gross entry N. This number is such that further entry would yield negative discounted profits. Therefore, N satisfies

$$(6) \qquad r^{-1}[P(N) - c(N)] - k(N) = 0.$$

For a unique solution N to eq. (6), we shall assume that $D^{-1}(\cdot) - c(\cdot) - rk(\cdot)$ crosses zero just once, as in Figure 2.[6]

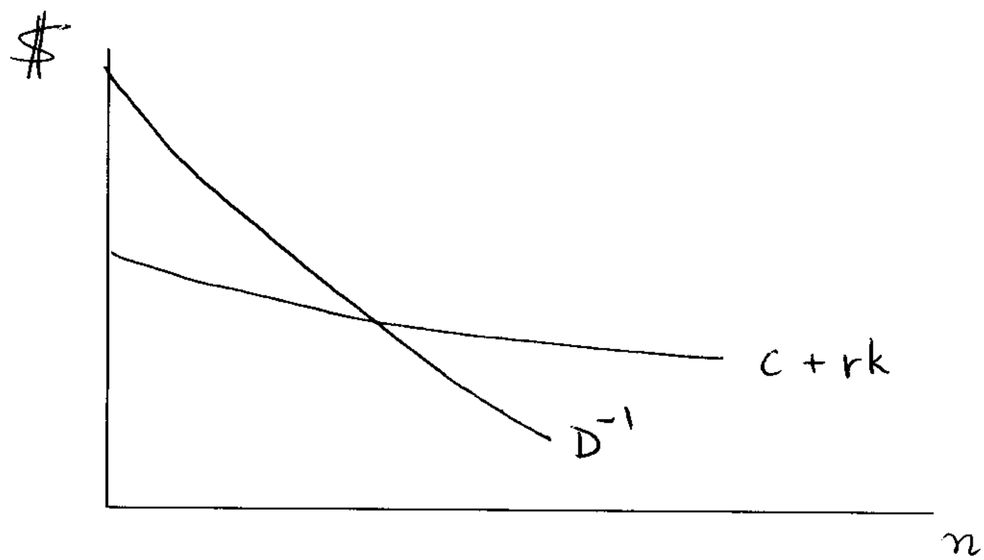

Figure 2

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[5] The evidence on this prediction is mixed. Klepper and Graddy (1985) find that the output of new products tends to increase monotonically. But both they, as well as Gort and Klepper (1982) find that the number of firms producing the new product first increases, and then tends to decline.

[6] This condition is valid for the case in which there is no exit. In general, a sufficient condition for uniqueness is that $P'(n) < c'(n)+rk'(n)$ for all n, which is equivalent to $c'(x)/[D'c'(x)+1] < c'(n)+rk'(n)$, so that convexity of $c(\cdot)$ is necessary to enable this inequality to hold.

Total gross exit $x[P(N)]$. Exit does not always occur in the model:

Proposition 4: The necessary and sufficient condition for a positive gross exit is that the average cost of the last entrant exceeds the marginal cost of the first entrant:

$$c(0) > c(N) + rk(N)$$

Proof: From (6), $p(N) < c(0)$, and the claim follows from Figure 1. Q.E.D.

When this condition is met, the initial entrant has a marginal cost that exceeds the final price, and will exit.

The next proposition and its corollary shows that the rate of entry cannot suddenly stop, but rather asymptotes to zero.

Proposition 5: If D' is bounded away from zero, and if k' and c' are bounded, then n_t has N as its limit, but never reaches it.

Proof: The assumptions of the proposition imply that for some $A > 0$, the right-hand side of eq. (5) is strictly less than $A[N-n]$, for all $n \in [0,N]$. Therefore $\dot{n} < A[N-n]$ for all $n \in [0,N]$. Hence if y_t solves the equation $\dot{y} = A[N-y]$ s.t. $y_0 = 0$, we know that $n_t \leq y_t$ for all $t \geq 0$. Thus, to show that $n_t < N$ for all t, it is enough to show that $y_t < N$ for all t ≥ 0. But $y_t = N(1-e^{-At}) < N$, for all t. Therefore $n_t < N$ for all t. Finally, since n_t is increasing and bounded, it must have a limit, and if its limit were anything other than N, (3) would be violated. Q.E.D.

Corollary: Since $\dot{n}$ goes to zero, net entry also goes to zero.

Diffusion. If we view entry as involving the use of new technology (a new type of machine), then n_t represents the cumulative diffusion of that technology.[7] Empirical evidence indicates that such diffusion is S-shaped as a function of time, as in Figure 3, where $\ddot{n}$ is at first positive, and then negative.

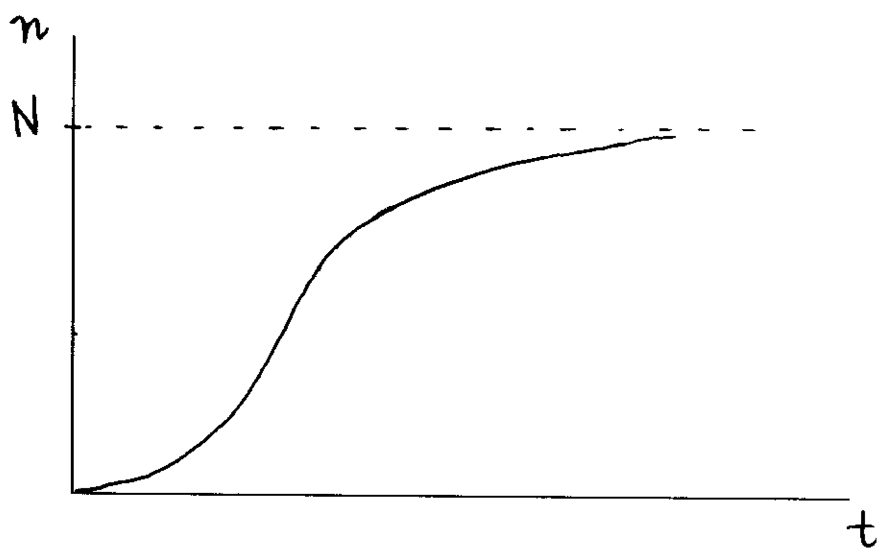

Figure 3

[7] If diffusion refers to the adoption of a new technology, then n_t is the right measure. On the other hand, if it refers to usage of a new technology then $n_t - x_t$ is a better measure. Empirical studies differ in the way they measure diffusion.

Proposition 5 implies that eventual concavity of n_t sets in as N is approached. In the case in which there is no exit, $T_t = \infty$ and $P(n) = D^{-1}(n)$. Differentation of eq. (5), and rearrangement, lead us to

Proposition 6: The diffusion curve is convex if and only if

$$c''(n) + r^{-1}k''(n) > \frac{[(D^{-1}(n))' - c'(n) - rk'(n)][c'(n) + r^{-1}k'(n)]}{D^{-1}(n) - c(n) - rk(n)}$$

This condition is more likely to be met early on, for two reasons: the denominator on the right hand side is larger, see Figure 2, and the degree of concavity in learning by doing is also higher.[8]

The next two examples both exhibit eventual concavity. Only the first exhibits initial convexity, since diminishing returns to learning by doing are absent in the second one. These examples assure zero marginal cost, hence there is no exit.

Example 1: (Arrow's constant elasticity). Let $k(n) = An^{-\alpha}$, and $D^{-1}(n) = Bn^{-\beta}$, $0 < \alpha < \beta < 1$. Solving (6) for N yields

$$N = (B/rA)^{1/\lambda\alpha}, \quad \lambda = (\beta - \alpha)/\alpha > 0.$$

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[8] Such convexity is a consequence of diminishing returns to learning by doing, which is natural on information-theoretic grounds.

The solution to (5), subject to the initial conditions $n_0 = 0$, is

$$n_t = N(1 - e^{-\lambda rt})^{1/\lambda\alpha}.$$

The solution is presented in Figure 4.

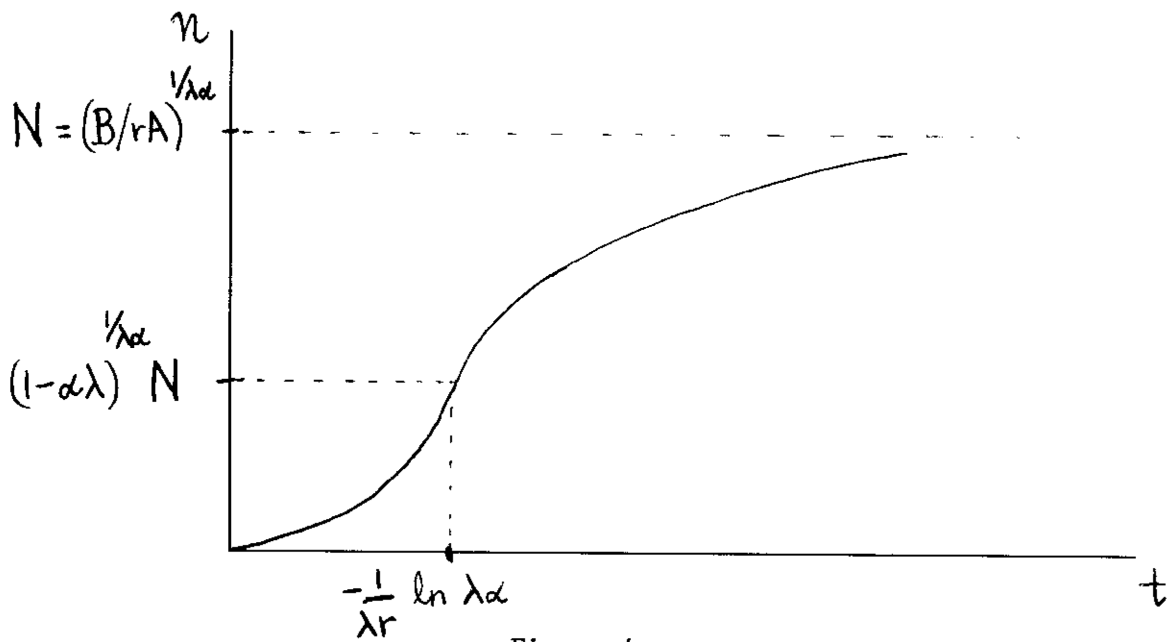

Figure 4

Notice that $\dot{n}_t = Bn_t^{1-\lambda\alpha}/\alpha A - rn_t/\alpha > 0$ for all $t > 0$. The diffusion path will be convex whenever

$$\ddot{n} = \dot{n}[(1-\lambda\alpha)n^{-\lambda\alpha}B/\alpha A - r/\alpha] > 0,$$

which holds for all $n \in (0,(1-\lambda\alpha)^{1/\lambda\alpha}N)$. The <u>mode</u> of the entry process is therefore $(1-\lambda\alpha)^{1/\lambda\alpha}N$, and is reached at time $-(1/\lambda r)\ln \lambda\alpha$.

Example 2: (linear). Let $k(n) = A - \alpha n$ and $D^{-1}(n) = B - \beta n$. For an interesting solution, we assume $B - rA > 0$, and $\beta - r\alpha > 0$. Then, (5) becomes $\dot{n}_t = (B-rA)/\alpha - (\beta-r\alpha)n_t/\alpha$ and

$$N = (B-rA)/(\beta-r\alpha) \quad \text{and} \quad n_t = N(1 - \exp\{-(\beta-r\alpha)t/\alpha\}).$$

Since $k'' = 0$ (and $(D^{-1})' < rk'$), the diffusion path is concave for all t, as indicated by Proposition 6.

Both of the above examples bring out the assertion of proposition 5, that N is never reached in finite time. Moreover, given that the slope of the demand curve exceeds that of rc (see Proposition 6), some diminishing returns to learning by doing (i.e., $k'' > 0$) are necessary to obtain the initially convex region for the diffusion process.

3. Welfare.

The equilibrium rate of entry is too low from the social viewpoint. The informational value of an entrepreneur's decision to enter spills over to future entrant and he is not compensated for it. Here, as in Arrow's model, learning does not take time. Rather, maximum cost-savings are attained so long as entrants move sequentially, at any speed. A planner would therefore send entrants in as fast as possible, subject to the constraint that the entrants move in sequence so that the advantages of learning can be reaped.

The planner's problem. Assume that c(n) and k(n) represent social costs. If the planner ever sends in more entrants than he uses for production, the idle entrants will clearly be the less efficient ones. If he sends N entrants in at an arbitrarily high rate, but if he does not use the first X of them for production, then the planner can "almost" attain[9]

$$W = \max_{N,X} r^{-1}\int_0^{N-X} D^{-1}(n)dn - \int_0^N k(n)dn - r^{-1}\int_X^N c(n)dn$$

subject to $0 \leq X \leq N$. The first term is the discounted integral under the demand curve. The second represents the fixed costs for all the N entrants, while the last expression is the discounted variable cost of production for those entrants that are used for production.

The optimal solution will clearly never involve $X = N$, but it may involve $X = 0$. The necessary condition for maximizing welfare, W, are (assuming an interior solution for N):

$$(7) \qquad \partial W/\partial N = D^{-1}(N-X) - rk(N) - c(N) = 0$$

and

$$(8) \qquad \partial W/\partial X = -D^{-1}(N-X) + c(X) \leq 0$$

Proposition 7: The equilibrium total gross entry and exit coincides with the planner's optimum.

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9 As the speed at which entrants are sent in approaches infinity, discounted social benefits can be shown to approach the expression below.

Proof: Let N^* and X^* denote the equilibrium magnitudes which satisfy (6) and (2), that is, (i) $P(N^*) - c(N^*) = rk(N^*)$ and (ii) $N^* - X^* = D[P(N^*)]$. From (ii) it follows that (7) is met at $N = N^*$ and $X = X^*$ if $D[P(N^*)] = D[rk(N^*) + c(N^*)]$. But this is implied by (i). To show that (8) is met, note that if $X^* = 0$, (8) is negative, because $c(0) < rk(N^*) + c(N^*)$ by Proposition 4, which together with (7) implies that (8) is strictly negative. When $X^* > 0$, from (1), $X^* = c^{-1}[P(N^*)]$. Substituting this into (8) yields $-D^{-1}[N^* - X^*] + P(N^*)$. But $D[P(N^*)] = N^* - X^*$ by (2). Q.E.D..

Remark: To attain W *exactly* is impossible. To get the integral under the demand curve immediately, the planner would have to send in a measure N of entrants immediately, "en masse". But then his total cost would be $Nrc(0) + (N-X)k(0)$, and that exceeds the costs in W.

The essential point is that any welfare that, under competition, starts to accrue at t, can be realized *immediately* under the planner's policy. The only social loss is in the timing of entry and exit.[10] Let us illustrate this for the simpler case in which there is no exit. The amount of welfare that, in the perfect foresight equilibrium, begins to accrue at t is

$$r^{-1}e^{-rt}[P(n_t) - rk(n_t) - c(n_t)]\dot{n}_t.$$

The term in square brackets is r^{-1} times the distance between the in-

[10] The time paths of entry and exit in Jovanovic (1982) were optimal because the learning that takes place in that model is entirely firm-specific, of no value to other firms.

stantaneous demand and cost, while $\dot{n}_t$ tells us how much the market is being enlarged at t (as $\dot{x} = 0$). Adding up over all entry-dates, we obtain, as shown in the appendix, the following social losses:

$$(9) \qquad L = r^{-1}\int_0^{\infty}(1-e^{-rt})[D^{-1}(n_t) - rk(n_t) - c(n_t)]\dot{n}_t \, dt.$$

<u>Example 3</u>:

In the linear case of example 2, we obtain, after some algebra,

$$W = (B-rA)^2/2r(\beta-r\alpha) \quad \text{and} \quad V = (B-rA)^2/r(2\beta-r\alpha)$$

where V is the amount of welfare generated in the perfect foresight equilibrium. As shown in the appendix,

$$L = W - V = \alpha(B-rA)^2/2(2\beta-r\alpha)(\beta-r\alpha) > 0.$$

Interestingly, while W and V both tend to infinity as r goes to zero, the difference is bounded and tends to $\alpha B^2/4\beta^2$. Of course, as $\alpha \longrightarrow 0$ and learning by doing becomes insignificant, the welfare losses disappear as well.

4. Conclusions

We have shown that diffusion is likely to be S-shaped in an environment in which homogeneous potential entrants can appropriate the benefits from learning by doing realized by earlier entrants. The equilibrium nature of the analysis highlights the role played by the declining path of the product price. Thus, the three critical ingredients of our theory are: learning by doing, spillovers, and perfect foresight.

Other implications of the hypothesis are: (a) A monotonically increasing industry output, (b) a monotonically decreasing product price, and (c) a decreasing rate of profit for each vintage of entrants.

The model is made simple and tractable at the cost of ignoring heterogeneity and strategic behavior. Strategic behavior and heterogeneity among potential adopters may be important, but analytically they blur our ability to recognize <u>other</u> forces in the economic system that may generate S-shaped diffusion curves. Our concern here has been to advance our hypothesis in the simplest possible way. Its empirical importance, relative to other possible explanations, is a matter for future work.

APPENDIX

Let V be the amount of welfare generated in the perfect foresight equilibrium, which, since there is no exit, is just

$$V = \int_0^\infty e^{-rt}\{\int_0^{n_t} [D^{-1}(z) - c(z)]dz - k(n_t)\dot{n}_t\}dt.$$

Proposition: The social loss W-V is given by (9).

Proof: The proof consists of changing variables in V from t to n using $t = t^{-1}(n)$. Note that $t^{-1}(0) = 0$ and $t^{-1}(N) = \infty$. Then, integrating V by parts results in

$$V = r^{-1}\int_0^N e^{-rt^{-1}(n)}[D^{-1}(n) - c(n) - rk(n)]dn.$$

Subtracting V from W, noting that N is the same for the two regimes, while $X = 0$ for both, and changing n back to t results in eq, (9).

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