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LEARNING-BY-DOING, MARKET STRUCTURE AND INDUSTRIAL AND TRADE POLICIES*

By PARTHA DASGUPTA *and* JOSEPH STIGLITZ

"Anything that we have to learn to do we learn by the actual doing of it: people become builders by building and instrumentalists by playing instruments." Aristotle, *The Nicomachean Ethics,* tr. by J. A. K. Thomson, Penguin Books (London), 1976, p. 63.

1. Introduction

LEARNING FROM experience is important in many industries, most especially in the early stages of their history. Productivity increases are realised not only as a result of the explicit allocation of resources to capital accumulation and research and development, but also often as a by-product of the process of production; that is, *learning-by-doing.*[1]

Learning gives rise to a special kind of intertemporal externality in production. It was used as an argument for the protection of infant industries, the idea being that in the absence of public intervention a domestic infant industry capable of learning would be stifled by foreign competition. (For an excellent presentation of the analysis and its limitations, see Baldwin, 1969, Wan and Clemhout, 1970 and Negishi, 1972).

To the best of our knowledge the literature developing the "infant-industry agrument" has supposed invariably that foreign manufacturers form a competitive industry and that learning has ceased there. Thus, the focus of concern is domestic learning.[2] But the literature would appear to have a central weakness: it has not explored how learning possibilities affect the *structure of domestic industry.* Without some understanding of this one cannot discuss appropriate government policies. The central purpose of this article is to study this issue and to analyse a few distinguished industrial and trade policies in the light of our findings.

* Research towards this article was initiated during the spring of 1984, while the authors were Visiting Professors at the Department of Economics, Stanford University and the Hoover Institution, Stanford, respectively, and it was completed while Dasgupta was Visiting Professor at Harvard University and Visitor to the National Bureau of Economic Research during the spring of 1987. We are most grateful to these institutions for making our visits both possible and greatly enjoyable, to Paul David for many stimulating conversations on the subject matter of this essay, and to Gene Grossman, Tim Kehoe, Kala Krishna, Eric Maskin, Hamid Sabourian and Mike Whinston and the referees of this journal for their incisive comments on an earlier draft. Financial support from the UK Economic and Social Research Council and the US National Science Foundation has made possible continuation of our research on technological change and market structure.

[1] Empirical studies of learning curves include the illuminating works of Asher (1956) and Alchian (1963) on airframe production, Zimmerman (1983) on nuclear power technologies and Lieberman (1984) on production and investment in chemical process industries. Hollander (1965) has investigated the phenomenon of learning in the technology of R&D.

[2] We are confining our attention to that part of the infant-industry literature which bases its argument on learning-by-doing, and are ignoring other reasons that have been invoked, such as inter-firm externalities unconnected with learning, and labour and capital market distortions. For a summary of these arguments see Haberler (1987).

Learning-by-doing involves a form of sunk cost. Production, leading to a gain in experience, is the cost which is sunk. Learning therefore manifests itself as an irreversibility in production possibilities. A key to our own analysis here will be a related feature, which is that unless learning spills over completely, instantaneously and costlessly among all rival production units, or unless at each date every unit faces strong diminishing returns to scale in production at some output levels, there are social wastes in having more than one production unit. In short, the industry is a natural monopoly. To see this, suppose that an industry in which production units have the potential for learning is socially managed. Suppose also that learning does not spill over completely. Suppose too that the average production cost faced by a production unit at any date is independent of its scale of operation at that date. In these circumstances it is socially preferable to have a single production unit producing specified amounts over time than to have two production units, each producing half the industry output at each date. The point is that in the latter case each unit learns less. This is a form of dynamic scale-economies in production and it suggests that if the industry were instead in the private sector it would assume an oligopolistic structure, not a competitive one; at least in the initial stages, when the scope for learning is large.

This much is plain enough. What is perhaps not so plain is the possibility that firm-specific learning encourages the growth of industrial concentration. To be specific, one expects that strong learning possibilities, coupled with vigorous comptetition among rivals, ensures that history matters (see Atkinson and Stiglitz (1969)), in the sense that if a given firms enjoys some initial advantages over its rivals it can, by undercutting them, capitalise on these advantages in such a way that the advantages accumulate over time, rendering rivals incapable of offering effective competition in the long run, unless they enter with technological innovations, or unless learning declines in its vigour.[3] Putting it another way, production of final output, one imagines, can itself be used as a preemptive move on the part of a firm to deter rivals from entering an industry or, in other circumstances, to make it less and less profitable for rivals to remain in an industry. Putting it in yet another way, 'learning' may well be used for the creation of entry-barriers, (see Scherer, 1980, pp. 250–252), or in other circumstances be used for discouraging rivals to remain in the industry. Whether this is a possibility depends upon whether the scope for learning is large and upon whether firms are far-sighted; but in ways that may not be obvious at first blush. The point is that even if the scope for learning is large at initial stages it must eventually become negligible: unit cost of production is, after all, bounded

[3] For a mathematical exploration of this view in a more general context, see Arthur (1983) and Arthur, Eromoliev and Kaniovski (1986). The late Gunnar Myrdal, Paul David and the late Nicholas Kaldor have emphasised this point of view in their writings on cumulative causation occurring in certain kinds of path-dependent processes. See e.g. Myrdal (1957), David (1985, 1987) and Kaldor (1985). The idea of cumulative causation has, of course, been central in evolutionary biology. For an excellent account, see Dawkins (1986, chapter 8).

below by zero. Thus, if oligopolists are far-sighted the scope for preemption on the part of advantaged firms is low because disadvantaged firms know that if they are patient and produce enough there will be oligopoly profits to be enjoyed in the distant future. But if firms discount the future at a large rate this argument would not appeal and the industry could then display growing concentration.

It is because of these presuppositions that one suspects in advance that the analyses of oligopolistic industries in the presence of learning-by-doing in Spence (1981) and Fudenberg and Tirole (1983) are misleading. These authors, first of all, postulate the number of firms in the industry. (Thus, industrial structure is given and fixed.) Secondly, they study industries where firms are identical. Thirdly, they restrict their analyses to symmetric market equilibria; that is, to equilibria in which oligopolists behave identically. These, for reasons we have mentioned, might well be exceptional features and in what follows we will model the industry in a variety of manners to show that the existence of strong learning possibilities can indeed result in the emergence of concentration. Thus, a central purpose of the initial positive analysis in our paper (Section 4) is to show that symmetric outcomes in the presence of strong learning possibilities can be misleading constructs. In order to concentrate our attention on dynamic scale-economies occasioned by the learning phenomenon we will assume, as in the works of Spence and Fudenberg and Tirole, that at each date each firm faces constant-returns-to-scale in production. We will investigate the emergence of concentration in Section 4.2 with the help of an example where, as in Spence and Fundenberg and Tirole, we postulate that a given number of firms are engaged in quantity competition *à la* Cournot. However, unlike the previous authors we will suppose that one of the firms possesses an initial cost advantage, possibly a small advantage. Our idea will be to show that if the scope for learning is large and if firms discount the future at a large rate, the initial advantage will accumulate over time in a way that will manifest itself in increased market share for the advantaged firm. In these circumstances the industry will experience growing concentration, leading possibly to monopoly, (Proposition 3). From the perspective of an analysis of the evolution of such an industry the assumption that firms are identical would in these circumstances be a bad one.

Now competition is relatively sluggish when a small group of firms compete in quantities. In Section 5 therefore we will study the consequence of vigorous competition among firms facing learning curves. The obvious way to model this is to allow firms to compete in prices for a homogeneous commodity, not in quantities. This will be the form of competition assumed in Section 5. In fact we will be concerned with an additional issue in Section 5, that of entry. We will begin, in Section 5.1, with the simplest case, where the number of firms in the industry is given. Firms will be assumed initially to face identical (unit) production costs. To one of them we will confer an advantage in the form of consumer loyalty. This will be the source of the asymmetry. We will show that in dynamic equilibrium the advantaged firm will be the sole active firm, constrained to earn zero present-value profits. The analysis here will be similar in spirit to that of contestable markets (see Baumol, Panzer and Willig, 1982), but with an important interpretive difference. Since our model possesses an explicit intertemporal structure occasioned by learning, the flow of profits enjoyed by the monopolist will not be constant. It will suffer losses in the early years in order to prevent its rivals from producing, with an anticipation of future profits. Typically, profits in dynamic equilibrium will increase over time, possibly rising eventually to monopoly levels.

This feature deserves emphasis. In the presence of learning a monopolist does not enjoy a constant flow of profits. The industry is not at a stationary state. It follows that the fact that at a mature stage a monopolist is seen to be earning positive profits is not, on its own, a reason for supposing that it has always done so, in particular that it has not suffered losses in the past. As the analysis of Section 5.1 will show, the advantaged firm in our model will initially price its product below (current) average production costs in order to assume monopoly status and reap monopoly profits later.

A shortcoming of the model in Section 5.1 is that all firms are assumed to be in the industry in advance of the analysis. In Section 5.2 we will therefore suppose that the industry possesses a single incumbent, the advantaged firm. We will ask if the threat of entry by rivals limits the powers of the incumbent. We will note in Proposition 5 that if entry on the part of firms is literally free the outcome is not predictable. There are multiple equilibria, ranging from the one in which the incumbent behaves as an unbridled monopolist to that in which its profits, in present-value terms, are diluted to zero. We will then argue (Proposition 6) that this multiplicity is spurious: the introduction of a positive entry cost, no matter how small, eliminates all but the first as an equilibrium outcome. The invisible hand is not merely weak, it is paralysed. The industry is an unconstrained monopoly.[4]

Sections 6–8 are concerned with (second-best) welfare economics in the presence of a learning curve. In Section 6 we will explore the kinds of intertemporal contracts which, if enforceable, would allow an industry with free entry to sustain a social optimum. We will identify them but will argue that the entire analysis breaks down if there is the smallest of entry costs.

This then leads us to explore the effects of government regulations (Sections 7 and 8). Learning-by-doing introduces a classic tension in sharp terms: unconstrained monopoly is not desirable for society, but oligopoly may well be worse, because in the process of sharing a market firms learn less and so future prices are higher. We argue that when applied to an industry in which there are strong learning effects the *per se* doctrine may well be undesirable. In Section 7 we will look at a few applications of the

[4] We should emphasize that the fact that even a small entry cost prevents competition from actually taking place when post-entry competition is expected to be fierce, is a general result, unconnected with learning-by-doing. (See Dasgupta and Stiglitz, 1987).

doctrine to illustrate this.[5] In Section 8 we will study a few distinguished types of government policy in the presence of foreign competition under several alternative circumstances. We will formalise a version of the infant-industry argument and will locate circumstances in which a temporary import ban leads to international Pareto improvement, (Section 8.1). Finally in Section 8.2 we suggest that if a *foreign* industry enjoys strong learning effects, stronger than domestic learning possibilities, and if domestic production costs are high, and if domestic demand for the foreign producer's output is a large fraction of his output, there is a case for temporary *import subsidies.* Such subsidies encourage greater foreign production and thus foreign learning. This in turn increases *domestic* benefits from lower import prices in the future.

Despite the prevalence of learning-by-doing the theoretical literature on its economic implications remains sparse.[6] Arrow (1962) and Kaldor and Mirrlees (1962) used variants of the idea to construct aggregate growth models of closed economies. In each of these contributions the economy was assumed to be competitive. We will, however, note below (Section 5) that this is a valid assumption *only* if firms can learn costlessly, completely and instantaneously from the experience of others; that is, if learning spillovers are complete.[7] This extreme assumption cannot be taken seriously. It flies against the face of evidence. Stated briefly our positive analysis aims at studying the consequences on market structure of the phenomenon of learning. Towards this we will, in Section 3 and 4.1, study in turn the effect of learning on a socially managed and privately monopolised industry, respectively. In Section 9 we will enumerate our conclusions. We begin (Section 2) with terms, notations and so forth.

2. Preliminaries

A single homogeneous commodity can be produced by n firms, or production units. Firms (or production units) are labelled i, j $(=1, 2, \ldots, n)$. The analysis that follows concerns for the main part, two production periods, $t = 0, 1$. The operative restriction is, however, not 'two', but 'finitely many', for we will note in passing that our results generalise readily to any finite number of periods. We want to distinguish the early, *infant,* phase of an industry from its later, *mature,* phase. The former is one during which learning is significant, the latter where in effect learning has ceased.

[5] See Scherer (1980), Chapters 19 and 20, for an account of anti-trust policies in the United States and in Western Europe, and in particular of the *per se* doctrine, taken to be implicit in the Sherman Act of the United States.

[6] For a general discussion of the issues that arise in the presence of learning-by-doing, see Scherer (1980), pp. 250–252.

[7] To be sure, an industry containing a very large number of identical firms engaged in quantity competition would be approximately competitive at a symmetric Cournot equilibrium even if learning were firm-specific. But in this case no firm would learn much, since each would produce a negligible amount at each date.

In order to concentrate on the industry in question we take it that income effects are negligible. Market demand for the commodity is given in each period by the downward sloping demand curve $p(Q)$, where Q is total output and p is the price at which the commodity is sold. (Nothing is gained by assuming shifting demand). Furthermore, we suppose that the $p(Q) \to 0$ as $Q \to \infty$. We assume that $p(Q)Q$ is strictly concave; that is, marginal industry revenue is a decreasing function of total output.

Let c_0^i be the unit cost of production for firm i in the first period. For simplicity of exposition we take it for all i, $p(0) > c_0^i > p(\infty) = 0$. Learning is based on *production* experience. By writing c_1^i for the unit cost of firm i in the second period ($t = 1$), we take it that

$$c_1^i = c_1^i\Big(Q_0^i + \alpha \sum_{j \neq i} Q_0^j\Big),$$

where Q_0^i (resp. Q_0^j) is the output of firm i (resp. firm j) in the first period. Here, α is a constant—the extent of learning spillover—and $0 \leqslant \alpha \leqslant 1$. Since there is learning, we assume that $c_1^i(\cdot)$ is a monotonically decreasing function, with $c_0^i(0) = c_0^i$. If $\alpha = 1$ learning is industry-wide and spillovers are complete, as in Arrow (1962), Kaldor and Mirrlees (1962) and Stokey (1986). This is far too extreme. At the other extreme is $\alpha = 0$; which means that learning is firm-specific. This is a good deal less questionable. It will transpire that all of our analysis is invariant to α, so long as $\alpha < 1$.

3. Nationalized industry and departures from marginal-cost-pricing

3.1 *Fully optimal pricing*

Suppose that the industry is a nationalized one. Assume first that losses can be covered by general taxation. Let $u(Q) = \int_0^Q p(\tilde{Q})\,\mathrm{d}\tilde{Q}$ and, without loss of generality let the social discount rate be nil. Assume for simplicity of exposition that all potential units are identical. If spillovers are incomplete (i.e. $\alpha < 1$) there ought obviously to be only one production unit, to take full advantage of learning. If $\alpha = 1$ it does not matter how many production units there are. Therefore we may as well assume there is only one.

The problem is then to choose Q_0 and Q_1 (output levels at $t = 0$ and $t = 1$ respectively) so as to maximize

$$u(Q_0) - c_0 Q_0 + u(Q_1) - c_1(Q_0)Q_1. \tag{1}$$

In what follows we will assume that this, and the monopolist's problem in Section 4, have bounded solutions. A sufficient condition for this is that $c_1(\infty) > 0$. Given this, maximisation of (1) yields the necessary conditions for optimality:

$$p(Q_0) = c_0 + c_1'(Q_0)Q_1, \tag{2a}$$

and

$$p(Q_1) = c_1(Q_0).^{8} \tag{2b}$$

Equation (2b) concerns optimal pricing policy in the mature phase. There is no more learning. Marginal-cost pricing is therefore the rule. But in the infant phase there is learning. And learning implies an intertemporal externality. Equation (2a) shows how to internalize this. It says that as long as there is a scope for learning the industry ought to price below current marginal cost. The industry thus makes losses in present-value terms. The optimal loss is covered by general taxation.

3.2. *Optimal pricing under revenue constraint*

Suppose that the industry must cover its losses over the planning horizon. In particular, it is to "balance its budget". Then the problem is to choose Q_0 and Q_1 so as to maximize (1) subject to the constraint

$$p(Q_0)Q_0 - c_0 Q_0 + p(Q_1)Q_1 - c_1(Q_0)Q_1 \geq 0. \tag{3}$$

Let λ denote the Lagrange multiplier associated with (3). Then, by writing $m(Q) \equiv p'(Q)Q + p(Q)$—($m(Q)$ is marginal revenue)—we can express the necessary conditions for optimality as:

$$p(Q_0) - c_0 - c_1'(Q_0)Q_1 = -\lambda[m(Q_0) - c_0 - c_1'(Q_0)Q_1] \tag{4a}$$

and

$$p(Q_1) - c_1(Q_0) = -\lambda[m(Q_1) - c_1(Q_0)], \tag{4b}$$

or equivalently as:

$$p(Q_0)[1 - \lambda\epsilon(Q_0)/(1+\lambda)] = c_0 + c_1'(Q_0)Q_1 \tag{5a}$$

and

$$p(Q_1)[1 - \lambda\epsilon(Q_1)/(1+\lambda)] = c_1(Q_0), \tag{5b}$$

where $\epsilon(Q) = -p'(Q)Q/p(Q)$, is the inverse elasticity of demand.

If the optimization problem (1) is a concave programme, constraint (3) is binding. In this case equations (4a)–(4b) [and equivalently (5a)–(5b)] reflect the Ramsey Rules for optimal departures from marginal-cost pricing. Given that $\lambda > 0$ we can conclude at once from equation (4b) that $p(Q_1) > c_1(Q_0)$, and therefore from (3), which is in fact an equality, that $p(Q_0) < c_0$. In other words, it is desirable to price the commodity above marginal cost in the mature phase so as to cover the losses incurred during the infant phase (equation (4a)) when learning occurs.

It is interesting to ask how the revenue constraint (3) affects optimal output over the two periods. Assume that $c_1(Q_0)$ is sufficiently convex so

[8] Primes denote derivatives.

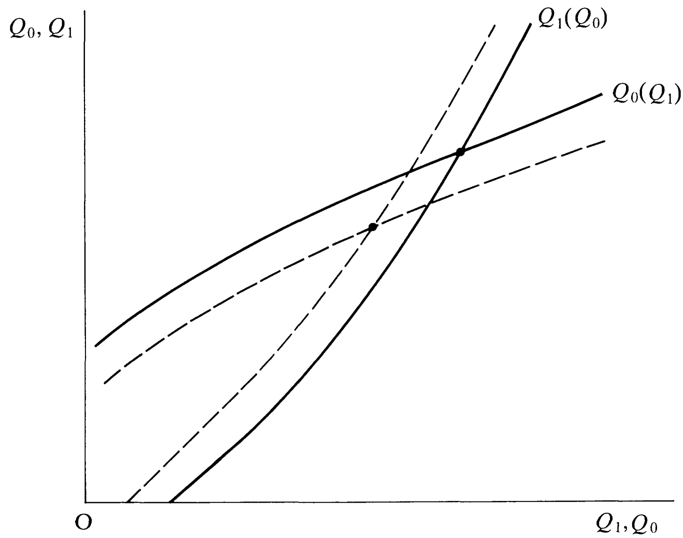

FIG. 1. Output levels of a nationalized industry with and without a revenue constraint.

that (1) is concave. Note then that if in the infant phase second-best output is lower than first-best output it must be so in the mature phase as well. In fact it is simple to confirm from equations (2a)–(2b) and (4a)–(4b) that second-best output is indeed lower than first-best output at $t = 0$. Therefore we have

Proposition 1: If a revenue constraint is imposed on a nationalized industry it will reduce output in each period.

The content of Proposition 1 can be seen diagrammatically in Fig. 1. The bold curve $Q_0(Q_1)$ is the solution of equation (2a), the dashed curve below it is the solution to equation (5a). They are thus optimal values of Q_0 as a function of Q_1, without and with the revenue constraint. Because of the greater benefit to learning, the higher is Q_1, the higher is Q_0. Equations (2b) and (5b) can likewise be thought of as defining the optimal value of Q_1 for each value of Q_0. They are drawn in Fig. 1, respectively, as the bold curve $Q_1(Q_0)$ and the dashed curve below it. The higher is Q_0 the lower is the marginal cost of production next period and therefore the larger is Q_1. The dashed curves are below the corresponding bold curves because the revenue constraint implies that for each value of Q_0, Q_1 is reduced, and for each value of Q_1, Q_0 is reduced.

4. Cournot competition among oligopolists and the emergence of monopoly

We now turn to a private industry. The simplest case to analyse is pure monopoly, the subject of Section 4.1. We will require the analysis for later purposes. In Section 4.2 we analyse Cournot-oligopolists.

4.1. *Monopoly*

We consider a monopoly facing no threat of entry by rivals. We assume that the capital market is perfect and (without loss of generality) that the rate of interest is nil. For reasons that are identical to those we raised in the case of a nationalized industry we may take it that the monopolist chooses a single production unit. Thus, the problem is to choose Q_0 and Q_1 so as to maximize:

$$p(Q_0)Q_0 - c_0Q_0 + p(Q_1)Q_1 - c_1(Q_0)Q_1. \tag{6}$$

This yields the necessary conditions,

$$m(Q_0) = c_0 + c_1'(Q_0)Q_1 \tag{7a}$$

$$m(Q_1) = c_1(Q_0), \tag{7b}$$

which can, equivalently, be written as

$$p(Q_0)[1 - \epsilon(Q_0)] = c_0 + c_1'(Q_0)Q_1 \tag{8a}$$

and

$$p(Q_1)[1 - \epsilon(Q_1)] = c_1(Q_0). \tag{8b}$$

Assume for the moment that $c_1(Q_0)$ is sufficiently convex, so that (6) is a concave function. From equations (7a) and (7b) we can conclude that the monopolist produces more in the second period than in the first (see Fudenberg and Tirole, 1983, p. 524). It can also be shown that a monopolist produces less than the first-best output level in each period (see Fudenberg and Tirole, 1983, p. 525). The question arises whether this remains true if monopoly output is compared instead to output level in a revenue-constrained nationalized industry. To answer this note from equations (5a)–(5b) and (8a)–(8b) that the second-best production rules are identical in form to the production rules of a monopolist, the difference in content being that the planner in the nationalized industry acts as though the elasticity of demand is higher. This allows us to assert

Proposition 2: A monopoly produces less than a revenue-constrained nationalized industry in each period.

From propositions 1 and 2 one notes that learning is greatest in an unconstrained nationalized industry. It is less in a revenue-constrained nationalized industry and it is least in a private monopoly.

Two further questions arise: (A) would a monopolist ever price below unit production cost so as to reduce future production cost dramatically? and (B) would a monopolist ever price the good in the second period in excess of first-period production cost? Answers to both are a 'yes' and, instead of seeking conditions under which the answers are a 'yes' we will merely formalize the questions, which will prove useful for subsequent exposition.

As regards (A), define

$$V(Q_0) \equiv \max_{Q_1} \{p(Q_1)Q_1 - c_1(Q_0)Q_1\}. \tag{9}$$

Let $\tilde{Q}_1(Q_0)$ be the solution of (9). It follows then that

$$V'(Q_0) = -c_1'(Q_0)\tilde{Q}_1(Q_0).$$

Now let $\hat{Q}_0$ be the solution of the equation $p(Q_0) = c_0$. At $\hat{Q}_0$ the gain in current profit due to a marginal increase in output is

$$m(\hat{Q}_0) - c_0 = -c_0\epsilon(\hat{Q}_0);$$

and the gain in the second period's profit is $V'(\hat{Q}_0)$. We conclude that the monopolist will price below unit cost in the first period if

$$V'(\hat{Q}_0) = -c_1'(\hat{Q}_0)\tilde{Q}_1(\hat{Q}_0) > c_0\epsilon(\hat{Q}_0), \tag{10}$$

and will price above unit cost if

$$V'(\hat{Q}_0) = -c_1'(\hat{Q}_0)\tilde{Q}_1(\hat{Q}_0) < c_0\epsilon(\hat{Q}_0). \tag{11}$$

(B) is easier to formalize. From equation (7a) we observe that

$$m(Q_0) = c_0 + c_1'(Q_0)\tilde{Q}_1(Q_0). \tag{12}$$

This yields the first-period output, Q_0^m, say. In other words, second-period price will exceed, or will be less than, first-period production cost, as

$$p(\tilde{Q}_1(Q_0^m)) > c_0, \tag{13a}$$

or

$$p(\tilde{Q}_1(Q_0^m)) < c_0. \tag{13b}$$

4.2. *Cournot duopoly*

We assume that the market lasts $T+1$ periods, where T is finite, but possibly large. We wish to analyse competition in quantities. We may as well assume then that the industry is a duopoly. Extension of the analysis to oligopoly is routine. In order to obtain explicit solutions we assume that the market demand curve at each date is linear. Thus,

$$p(Q) = A - BQ; \qquad A, B > 0 \tag{14}$$

Furthermore, we take it that so long as production cost is positive, the learning curve is linear. In short,

$$c_t^i = \max\left\{0, c_0^i - \beta \sum_{\tau=0}^{t-1} Q_\tau^i\right\}, \qquad \text{for } i = 1, 2,\ T \geqslant t \geqslant 1, \qquad \text{where } \beta > 0 \tag{15}$$

The learning curve embodied in (15) has two parameters, c_0^i and β. The former measures the extent to which learning will prove useful and the latter the extent of the rate of learning possibilities. (15) captures in a sharp way the idea that learning ceases after finite accumulation of experience. Diminishing returns to learning set in very dramatically once unit cost has fallen to zero.

Suppose one of the firms (say, firm 1) enjoys an initial cost advantage over its rival. We want to study the evolution of the industry when the firms behave non-cooperatively. Suppose first that T is large and that firms discount future profits at a low rate. Then it is clear that in equilibrium the disparity between the firms will vanish in the long run. The reason is that with finite output even the disadvantaged firm (firm 2) can reduce its production cost to zero. There are duopoly profits to be enjoyed from that point onwards. With a long horizon and a low discount rate the present-value of such profits is large. Clearly then it pays both firms to produce. In the long run market shares will equal each other.

But what if the discount rate is large? The above argument then no longer applies and the disadvantaged firm (firm 2) may well choose to withdraw from the market gradually as the cost difference between it and its rival widens. Here is how this might happen.

If the discount rate is large each firm cares mostly about current profits. Given that firms compete in quantities the advantaged firm (firm 1) will therefore produce more than its rival in the first period. Since the learning curve is linear, the reduction in unit cost for firm 1 will be greater than that for firm 2. Thus the disadvantaged firm will continue to be at a disadvantage, in fact even more disadvantaged. And so on. The problem then is to identify circumstances where this leads to the growth of concentration. We do this by studying the obvious limiting case, where firms are fully myopic; that is, where firms discount future profits at an infinite rate.

Let Q_t^i denote the (Cournot) equilibrium output of firm i ($i = 1, 2$) at date t. Assume that it is positive. Then, on using (14), routine calculations yield:

$$Q_t^1 = [A + c_t^2 - 2c_t^1]/3B, \quad \text{and} \quad Q_t^2 = [A + c_t^1 - 2c_t^2]/3B \tag{16}$$

But from (15) we know that

$$c_t^i = \max\,[c_{t-1}^i - \beta\, Q_{t-1}^i, 0] \tag{17}$$

Assume that c_t^i is positive. Assume further that equilibrium output levels at

$t+1$ are also positive. Then it is simple to confirm that

$$\begin{aligned} Q_{t+1}^1 &= [9B^2Q_t^1 + \beta A - 5\beta c_t^1 + 4\beta c_t^2]/9B^2 \\ Q_{t+1}^2 &= [9B^2Q_t^2 + \beta A - 5\beta c_t^2 + 4\beta c_t^1]/9B^2 \end{aligned} \tag{18}$$

From (16) we know that $Q_t^1 > Q_t^2$ if $c_t^1 < c_t^2$ by hypothesis, Q_t^1 and Q_t^2 in (16) are both positive. It follows from this and (18) that

$$Q_{t+1}^1/Q_{t+1}^2 > Q_t^1/Q_t^2, \tag{19}$$

if $c_t^1 < c_t^2$, or in other words, that the concentration ratio increases so long as there is a cost differential between the firms.

The foregoing analysis assumes that both firms are active at both periods. Is it possible for the concentration ratio to go to infinity, with the disadvantaged firms leaving the industry? Here is an account of how this can happen.

Let $\Delta = c_0^2 - c_0^1 > 0$ denote the initial cost difference. For both of them to produce at the initial date it follows from (16) that $A + c_0^1 > 2c_0^2$, or in other words that

$$A - c_0^1 > 2\Delta \tag{20}$$

Using (16) in (18) we note that

$$9B^2Q_1^2 = 3B[A + c_0^1 - 2c_0^2] + \beta[A + 4c_0^1 - 5c_0^2] \tag{21}$$

But now suppose $A - c_0^1 < 5\Delta$, which is perfectly consistent with (20). Then, while the expression within the first pair of brackets in the right hand side of (21) is positive, that within the second pair of brackets is negative. If β is 'large', Q_1^2 in (21) is not positive. But this is another way of saying that the disadvantaged firm drops out, it ceases to produce: the cost differential is altogether too much in the second period. We conclude with

Proposition 3: If firms discount the future at a high rate and the scope for learning is approximately constant, then so long as learning has not ceased an industry will display growing concentration. If the rate of learning is large then under certain circumstances the industry becomes a monopoly in the long run.

These possibilities are shown in the phase diagrams in Figs. 2 and 3 where, for convenience, we have assumed time to be continous. In each of the figures firm 1 is assumed to enjoy an initial cost advantage over its rival. In Fig. 2 industrial concentration increases until firm 1 ceases to learn any further. Firm 2 then catches up gradually—that is, industrial concentration declines—until it too ceases to learn. From this date the rivals produce constant and equal quantities for the market.

Figure 3 depicts a different case. Here, industrial concentration increases all the way to an eventual monopoly. In finite time the cost differential becomes sufficiently large to force firm 2 to withdraw from the market.

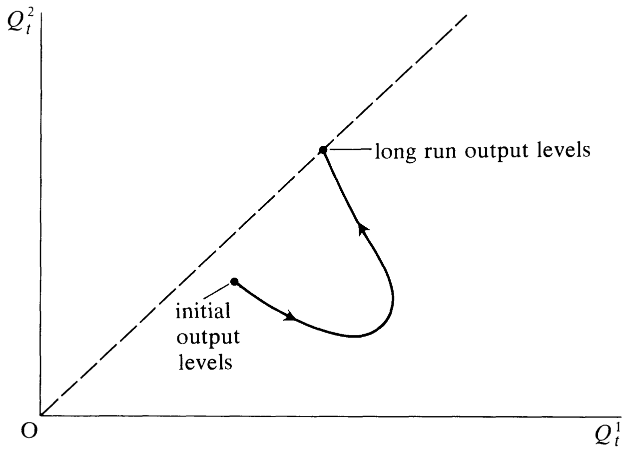

FIG. 2. Evolution of market shares, 1: the persistence of duopoly.

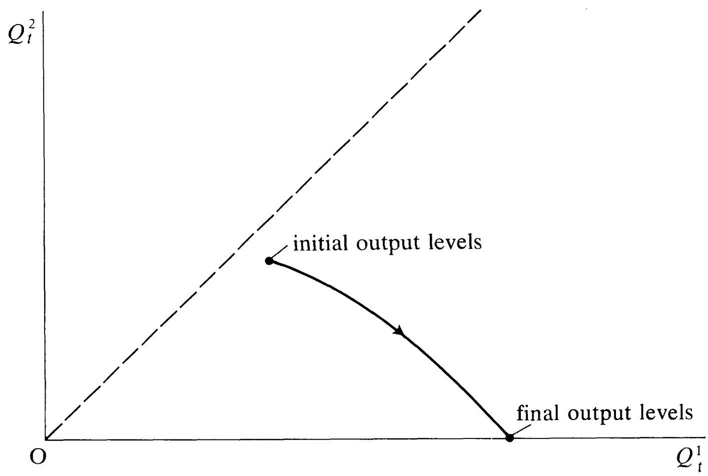

FIG. 3. Evolution of market shares, 2: the emergence of monopoly.

5. Bertrand competition among oligopolists

5.1. *Exogenous market structure*

There are two firms in the industry, the initial unit production cost for each being c_0. There are two dates $t=0$ and $t=1$.[9] For ease of exposition we take it that learning is firm-specific.[10] At each date the firms are engaged

[9] The analysis readily generalises to many periods.

[10] It is easy to confirm that the arguments readily generalise to the case where there is spillover in learning, so long as it is not complete. The analysis of this section is thus valid for $0 \leq \alpha < 1$.

in price competition *à la* Bertrand. Since they produce identical goods the firm setting the lower price captures the entire market. The question of how they share the market when they charge the same price is more delicate. For technical reasons (see footnote 11 below) we will make the seemingly awkward assumption that one of the firms (say firm 1) gets to supply the entire market should the firms set the same price. It would, on the face of it, seem more reasonable to assume that the firms divide the market, say evenly, in the case of a tie (see Section 7). But we want to introduce an asymmetry among firms and some such notion as a form of "consumer loyalty" is one way of doing it.[11]

In what follows we do *not* suppose that the monopoly profit function, expression (6), is necessarily concave. In order, then to characterise (subgame perfect) equilibrium in this market, define

$$Q_1^*(Q_0) \equiv \arg\max_{Q_1} [p(Q_1) - c_1(Q_0)Q_1], \qquad \text{subject to } p(Q_1) \leq c_0.^{12} \quad (22)$$

Next, define Q_0^* as the largest solution of the zero-profit condition

$$p(Q_0)Q_0 - c_0Q_0 + p(Q_1^*(Q_0))Q_1^*(Q_0) - c_1(Q_0)Q_1^*(Q_0) = 0.^{13} \quad (23)$$

It is now a simple matter to confirm

Proposition 4: The duopoly market possesses a unique subgame-perfect equilibrium. In equilibrium the advantaged firm (firm 1) charges $p(Q_0^*)$ and $p(Q_1^*(Q_0^*))$ for its product at dates $t=0$ and $t=1$, respectively, and serves the entirely market. The rival charges $p(Q_0^*)$ and c_0 for its product at the two dates and produces nothing.

Competition from the rival drives the maximum profits of the advantaged firm to zero. But notice that (22) and (23) imply $p(Q_0^*) < c_0$. In other words the advantaged firm is forced to incur losses at the infant stage. If the price constraint in (22) is not binding the producer earns monopoly profits at the mature stage.

5.2. *Potential competition*

What is the effect of potential competition on an incumbent's behaviour? To analyse this we alter the structure of the previous model and assume that before the duopoly game is played the rival is not in the industry. The incumbent, by definition, *is*. Whether the rival enters is a matter to be

[11] If a 50–50 sharing rule is postulated an equilibrium in pure strategies does not exist. But an ϵ-equilibrium in pure strategies does exist and, in fact, the equilibria we will compute in this section of the paper with the asymmetric sharing rule are approximately the same as ϵ-equilibrium with the symmetric sharing rule (See Section 6).

[12] $Q^*(Q_0)$ is a function—not a correspondence-because of our assumption that (gross) current revenue is strictly concave in output.

[13] Equation (23) may have multiple solutions, since (6) is not necessarily a concave function of Q_0 and Q_1.

deduced. First period unit production cost for the incumbent is c_0. Should the rival enter in the first period it too can produce at unit cost c_0. If it does not enter, by definition it cannot compete in the market. As before, learning is firm specific.

Entry is free. But we suppose that exit is prohibited. (The reader can easily calculate the consequences of making exist costless.) Moreover, the rival has the option of entering in the second period should it not enter in the first. (It can, to be sure, choose never to enter.) The moves are thus as follows. The rival decides first whether to enter. Should it enter, the two engage in price competition thereafter and in each period each of the firms supplies the demand the market makes of it. (We take it that the incumbent captures the entire market at any date the firms set the same price. The motivation behind our imposing this asymmetry is no different from the one in Section 5.1). If, on the other hand, the rival does not enter the incumbent is free to act as a monopolist. However, the rival has the option of entering at the start of the second period. Should it choose to enter, the two then engage in price competition. (But note that in this case the rival suffers from a cost disadvantage, since its unit cost of production is still c_0.)[14] If the rival refrains from entering even in the second period the incumbent is free to act as a monopolist once again.

The central result, which is as simple to prove as Proposition 4, is this.

Proposition 5: If entry is free the market possesses three subgame-perfect equilibria:

(i) an *instant-entry* equilibrium, where the rival enters at once;
(ii) a *delayed-entry* equilibrium, where the rival enters at the start of the second period; and
(iii) a *no-entry* equilibrium.

The rival earns nothing and produces nothing in any equilibrium. The incumbent can rank equilibria, preferring most of all (iii) and least of all (i), where it earns nothing.

We now proceed to characterise equilibrium, and the resulting profits the firms earn in each equilibrium. To do this, define

$$Q_0^{**} \equiv \max\left[\arg\max_{Q_0} [p(Q_0)Q_0 - c_0Q_0 + p(Q_1^*(Q_0))Q_1^*(Q_0) - c_1(Q_0)Q_1^*(Q_0)]\right] \quad (24)$$

where Q_1^* (Q_0) is defined in (22). Next, denote as Q_0^m and Q_1^m the solution

[14] Bhattacharya (1984) analyses a contrasting case, where the potential entrant can invest to reduce its production cost prior to entry.

of equations (8a) and (8b)-monopoly output levels in the two periods. It is then simple to confirm that at the no-entry equilibrium the incumbent's strategy is to charge $p(Q_0^m)$ for its product in the first period and announce its intention to charge $p(Q_1^m)$ in the second period should the rival not enter and charge $p(Q_1^*(Q_0^m))$ should the rival choose to enter. At the no-entry equilibrium the rival does not enter and so the incumbent earns monopoly profits.

Similarly, it is simple to confirm that at the delayed-entry equilibrium the incumbent sets its price equal to $p(Q_0^{**})$ in the first period and announces its intention of charging $p(Q_1^*(Q_0^{**}))$ in the second period should the rival enter in the second period and to charge the second period monopoly price should the rival not enter. The rival's strategy is to enter in the second period and charge c_0. Finally, the strategies supporting the instant-entry equilibrium are identical to those described in Proposition 4. The remaining parts of Proposition 5 are equally simple to confirm.[15]

How is the analysis affected if the number of periods exceeds two? Not much. If there are T periods, and if learning never ceases, then with free entry there are $T+1$ subgame-perfect equilibria in each of which the rival earns nothing, as in Proposition 5, and which can be ranked by the incumbent, with the no-entry equilibrium being the most preferred one.

We conclude therefore that potential entry is not potent enough to ensure that the incumbent's profits are driven to zero. In fact however one suspects that the no-entry equilibrium is the only one which should command our attention, a suspicion which is confirmed if we assume that entry is not costless. So we suppose that the rival must incur a (sunk) cost, $k(>0)$ in order to enter. We can now easily confirm

> *Proposition* 6: The market possesses a unique equilibrium if the rival has to bear a cost for entry. In equilibrium the rival does not enter and the incumbent acts as an unconstrained monopolist.[16]

Proposition 6 displays in a sharp form the idea that an initial advantage can be decisive in the long run. The sharpness is due to the postulate of price competition among firms involved in the production of a homogeneous commodity. If the commodities are not homogeneous one would require a non-negligible entry cost to eliminate all equilibria other than the one in which the rival never enters.

[15] If inequality (13b) holds, then in terms of profits to the incumbent there *is* no difference between the delayed-entry and no-entry equilibria, because in this case the constraint in (14) is not binding when $Q_0^m = Q_0$. If on the other hand (13a) holds this is not so, and the incumbent earns less at a delayed-entry equilibrium.

[16] Speaking formally, a small entry cost is a means by which one can eliminate what are really implausible equilibria. In our present model it eliminates the instant-entry and the delayed-entry strategies on the part of the rival as equilibrium strategies. It serves much the same role as would certain types of "trembling-hand" on the part of the incumbent.

6. Long term contracts

The discussion in the previous section has established two central points. First, in the presence of entry costs potential competition poses no threat to an incumbent when, as in our model, post-entry competition is expected to be fierce. (The more fierce post-entry competition is expected to be, the smaller is the entry cost that is sufficient to act as a barrier to entry). Second, even the zero-profit outcome of the instant-entry equilibrium has nothing obvious to commend it; it would not sustain the revenue-constrained optimum of Section 3.2. We now take up this second point, and see that what prevents the instant entry equilibrium from achieving the revenue-constrained optimum is an absence of long term contracts. In the next section we will look at the policy implications of the first point. In what follows we return to the two-period construct.

Suppose, as in Section 5.1, that both firms are already *in* the market. Next suppose that individuals can sign long-term contracts. A firm would then offer an individual price quotations for both periods, and the customer would agree (and this would be a binding agreement) to accept delivery of so many units in the first period and so many in the second. The firm offering the best contract would presumably attract all the customers. We now have to specify the game. We may, as in the previous section, suppose that the firms move simultaneously. In which case we need to assume either that one of the firms is privileged and gets the whole market whenever they offer the same contract, or that one of the firms is not an optimizer but is satisfied so long as it is in the neighbourhood of maximum profit. (Otherwise there is no equilibrium in pure strategies.) Alternatively we may follow the contestability theory route and award one of the firms the first move, the other firm being the follower. In what follows we continue to assume that firms move simultaneously and award one of the firms the entire market in case of a tie.

Suppose that all consumers are identical. They therefore agree on what is the best contract. If firms can charge non-linear prices the full optimum of Section 3.1 will be sustained at an equilibrium. Each firm would offer to sell the commodity at prices given by equations (2a) and (2b) and in addition charge a fixed-fee just large enough to ensure that profits are zero. If non-linear prices are not feasible, market equilibrium would sustain the revenue-constrained optimum of Section 3.2. Here, firms would offer the Ramsey prices given by equations (5a) and (5b).

Such long term contracts do not generally exist. But were they to exist they would themselves represent a barrier to further entry for firms who happen subsequently to develop a new and better process of manufacture, or produce a better quality product. In addition, one must not overlook the fact that the signing of such contracts entails some (sunk) costs, and this, as we noted in Section 5.3, is an important barrier to entry! We are then back with Proposition 6: entry costs, however small, are a barrier to actual competition.

What are then the policy implications of this for an industry where there is learning-by-doing? We turn to this.

7. The *per se* doctrine

Anti-trust policies have taken a wide variety of forms. But they would all appear to flow from a common attitude, that if there is a single large firm in an industry it must *per se* be bad. Unless there is complete spillover in learning this attitude is questionable, because the industry is a natural monopoly when spillovers are less than complete and if there are insufficient diminishing return in each firm. If learning effects are significant monopoly is not necessarily the worst form of market structure. Duopoly (or oligopoly) outcomes may be worse for society: the infant phase of an industry may be prolonged. We conclude that a ruling which sets an upper limit to the share of the market that any single firm can enjoy may be deleterious.

The foregoing discussion addressed the possibility of welfare loss due to the dismantling of a monopoly. We turn next to another kind of anti-trust ruling that can reduce welfare. This is when the government considers a firm to be engaged in predatory behaviour if it prices its product below it current marginal cost. Now, we have noted in Section 3 that a monopolist, even when unconcerned about entry, may charge a price lower than *current* marginal cost (condition (10)). The question is whether the regulatory authorities can obtain information that allows it to distinguish predatory pricing from monopoly pricing in the presence of strong learning effects. If they cannot, and they force the monopolist to charge c_0 in the first period, entry would still be deterred if there is a small entry cost. So the industry would remain a monopoly, the monopolist would earn lower profits and would charge a higher price in both periods. (In the second period also, because there would then be less learning.) The policy in question hurts all.

8. Trade policies

8.1. *An infant industry argument*

The infant-industry argument begins, for the most part, with the assumption that foreign producers are competitive and that in particular, learning has ceased among them. So let $\bar{c}$ be the foreign unit production cost. Assuming transport costs to be nil this is then the world price for the commodity. As before, let c_0 be the domestic producer's unit production cost in the first period and $c_1(Q_0)$ its unit cost in the second period when Q_0 is its initial output. To have a pertinent problem we take it that $c_0 > \bar{c}$ and that there exists some $\hat{Q} > 0$ such that $c_1(Q) < c$ for all $Q \geqslant \hat{Q}$. We denote domestic demand in each period by the function $p_d(Q)$ and world demand in each period by the function $p_w(Q)$.

We take it that there is a single domestic firm. (Proposition 6 provides a justification for this.) Will it be active if there is no government intervention? It will, if it can earn positive present-value of profits despite the presence of the competitive foreign sector. To formalise this, write

$$\pi \equiv \max_{Q_0, Q_1} [p_w(Q_0)Q_0 - c_0Q_0 + p_w(Q_1)Q_1 - c_1(Q_0)Q_1]$$
$$\text{subject to } p_w(Q_0), p_w(Q_1) \leq \bar{c} \quad (25)$$

The domestic firm will certainly produce, and indeed monopolise the world market—through limit pricing perhaps-if $\pi > 0$. It will not produce at all if $\pi < 0$. So let us assume the latter. Is there then a case for government intervention?

Rather than explore optimum government policies we will in what follows, ask under what condition a temporary protection, in the form of import ban, is desirable. For simplicity we will consider the case where an import ban is imposed as an infant protection.[17]

Let $\bar{Q}_d$ be the solution of $p_d(Q) = \bar{c}$. Since $\pi < 0$ we note that under *laissez-faire* domestic welfare, S, is

$$S \equiv 2[u_d(\bar{Q}_d) - \bar{c}\bar{Q}_d], \quad \text{where} \quad u_d(Q) = \int_0^Q p_d(\tilde{Q})\,\mathrm{d}\tilde{Q} \qquad (26)$$

If an infant-industry protection is offered to the domestic firm it is not constrained by the international price when it produces for the domestic market. Without loss of generality we can assume that the firm does not find it in its interest to compete in the international market in its infant phase. In its mature phase it may, of course, wish to compete. If it does, it will monopolise the world market. Naturally, we will consider the case where it will wish to monopolise the world market in the second period. Thus write

$$\bar{\pi} \equiv \max_{Q_0, Q_1} [p_d(Q_0)Q_0 - c_0Q_0 + p_w(Q_1)Q_1 - c_1(Q_0)Q_1]$$
$$\text{subject to } p_w(Q_1) \leq \bar{c}. \quad (27)$$

Notice that $\bar{\pi}$ may be positive even when π is negative. It follows from (27) that the home producer can be coaxed into activity by a temporary import ban if $\bar{\pi} > 0$. In this situation the domestic producer during infancy serves only the home market and monopolises the world market when it matures.

But does the import ban increase welfare when compared to free trade? It can. To see when this is so, let $\bar{Q}_0$ and $\bar{Q}_1$ be the solution of (27) and consider circumstances where the constraint in (27) is not binding; that is $p_w(\bar{Q}_1) < \bar{c}$. Thus there are gains to domestic purchasers in the second period as a consequence of this protection, and this may be sufficient to warrant the protection. Formally, define $\bar{Q}_1^d \equiv p_d^{-1}(p_w(\bar{Q}_1))$ to be domestic

[17] We could as well study the desirability of a domestic production subsidy during infancy.

sales in the mature phase following infant-industry protection. Then domestic welfare, $\bar{S}$, under protection, is

$$\bar{S} = u_d(\bar{Q}_0) - c_0\bar{Q}_0 + u_d(\bar{Q}_1^d) - c_1(\bar{Q}_0)\bar{Q}^d + [p_w(Q_1) - c_1(\bar{Q}_0)](\bar{Q} - \bar{Q}_1^d). \tag{28}$$

Since $\bar{Q}_1^d > \bar{Q}_d$, there are circumstances where $\bar{S} > S$; that is, where the temporary import ban is better for the domestic economy than is *laissez-faire*. But $p_w(\bar{Q}_1) < \bar{c}$. It follows that foreign consumers also gain in the second period as a result of the protective policy. We conclude that the import ban is a Pareto improvement.

All this assumes that the domestic monopoly is unable to sign long term contracts with domestic consumers. If it could, there would be no need for infant protection, because the infant could look after itself. It is when for whatever reason such contracts cannot be implemented that the case for government intervention arises. In our example consumers stand to gain in the second period from entry by the infant, but the infant cannot appropriate the benefits. So under free-trade profits are negative for the infant. An import ban allows consumers to pay for their second period gains in the first period. We are not claiming that an import ban is a second-best. We have merely sought the kinds of consideration which make a ban an improvement on free trade.

8.2. *Foreign learning and import subsidies*

Thus far a variant of the classical infant industry argument. But it is not unusual for a home country to face a foreign monopoly which is still learning. Should the home government encourage domestic production? The answer depends on several factors. If the domestic industry faces a learning curve as well and, in particular, if domestic learning possibilities are strong there is an argument in favour not dissimilar to the one we have outlined in the previous sub-section. In addition, dependence on the foreign monopoply means that such profits as occur in the home market are repatriated abroad. As against this, we have to recognize that with an international duopoly both firms learn less. This affects domestic welfare.

Consider the case where domestic production is far too costly. The commodity has then to be imported from the foreign monopolist. Suppose, to highlight the point we wish to make, the foreign monopoly is a nationalised firm. Its production plan is based on national welfare and does not include the welfare of the importing country. It follows that from the point of view of the latter there will be insufficient learning. An import subsidy suggests itself. If learning effects are strong enough and the importing country large enough a judicious subsidy on imports would coax greater production from the foreign monopoly and thus lower future prices sufficient to justify it.[18]

[18] Gatsios (1987) has developed a detailed analysis of this possibility and of the desirability of customs unions in the presence of scale-economies in production.

Often, one sees trade among differentiated products. Learning, as we have seen, provides a reason why a firm inolved in production is a natural monopoly. If countries are more or less equally placed in terms of the ability to learn from the production of these differentiated goods there is a case for each country specialising in some variety (possibly more than one variety). The consideration outlined in the previous paragraph implies that each nation ought in addition to offer an import subsidy on each variety it imports, as part of a mutual agreement within a Customs Union.

9. Conclusions

Learning-by-doing implies dynamic scale economies in production. It involves a form of sunk cost. Production during the infant phase assumes partially the role of investment. Such sunk costs are discretionary. In this paper we have analysed the implications of learning on the structure, conduct and performance of an industry. Apart from any details that may be of interest our main findings can be summarized as:

(1) There is a tendency towards the emergence of dominant firms—and thus concentration—when learning possibilities are powerful. This is so even when there is competition among rivals of near-equal strength.

(2) If the market is "contestable" the present-value of profits earned by the dominant firm is negligible. But because of learning, time enters in an essential way. Early losses incurred by the dominant firm are matched by subsequent profits. Data on profits earned in the mature stage are therefore not a reliable guide to the underlying characteristics of the industry.

(3) The presence of small entry costs can ensure that the industry is a pure monopoly; that is, such costs can render potential competition totally ineffective.

(4) The *per se* doctrine is questionable when learning effects are powerful. It may well be suboptimal to set a predetermined share of the market as an upper limit for the incumbent.

(5) During the learning phase even a protected private monopolist may wish to price its product below its current unit production cost. Thus if an incumbent firm does price its product below production costs it does not follow that it is engaged in predatory pricing.

(6) A large importing country may find it in its interest to impose import subsidies if the foreign learning curve is steep and if domestic production costs are high.

And finally,

(7) There are circumstances in which the traditional infant industry argument is valid; that is, in which welfare is higher with an import ban than with free trade.

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