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## THE LEARNING CURVE, DIFFUSION, AND COMPETITIVE STRATEGY

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*This paper explores the implications of the learning curve for competitive strategy under a range of assumptions regarding competition and the nature of the learning process. A game-theoretic model is used to examine how the learning rate and information diffusion affect entry barriers, profits, and price dynamics.*

### INTRODUCTION

The 'learning curve' (or 'experience curve') has become a central concept in corporate strategic planning. It provides the theoretical rationale for many corporate portfolio planning techniques and is frequently used to justify aggressive pricing of new products. The popularity of the learning curve as a tool for business strategy reached a peak in the mid-1970s, based on efforts by the Boston Consulting Group to apply to business strategy what had previously been a tool for production planning (Boston Consulting Group, 1972; *Business Week*, 1973). Firms were advised to expand output and acquire market share in order to gain a long-term cost advantage over rivals. However, the purported benefits of such learning curve-based strategies often failed to materialize, and the concept lost favor during the late 1970s (Kiechel, 1981; Day and Montgomery, 1983).

This paper explores the implications of the learning curve for competitive strategy under a range of assumptions regarding competition and the nature of the learning process. The paper begins by considering the optimal decision rules which apply when a learning curve is present. Then results of a dynamic model of competitive equilibrium are reported. This model is used to study how the rate of learning and information diffusion affect entry barriers, profits and the

time path of price and output. Finally, some extensions and implications of the results are suggested. The aim of the paper is to use theoretical models to explore issues of practical significance for strategic planning industries where the learning curve is an important factor. The effects of information diffusion are given particular emphasis, since these have a critical impact on optimal strategy but have generally been overlooked in the past.

### EMPIRICAL EVIDENCE ON THE LEARNING CURVE

There is now considerable empirical evidence documenting the existence of learning curves in a wide variety of industries. Learning curves have typically been found to conform to the functional form

$$c(x) = ax^{-b} \quad (1)$$

where  $c(x)$  is marginal cost,  $a$  is the cost of the first unit,  $x$  is cumulative output, and  $b$  is the learning "elasticity", which defines the slope of the learning curve.<sup>1</sup> This simple model has been

<sup>1</sup> The learning curve 'slope', as conventionally defined, is the level to which costs fall each time cumulative output doubles. For example, an '80 percent learning curve' implies that costs fall to 80 percent of their previous level for each doubling of cumulative output. The learning curve slope is related to the learning elasticity,  $b$ , by the formula,  $\text{slope} = 2^{-b}$ .

observed to fit most empirical data quite well, although the functional form has never been subjected to a rigorous specification test.

Given that learning curves based on cumulative output have little basis in neoclassical economic theory, there have been numerous efforts to attribute the learning effect to more conventional economic factors. Several empirical studies have tested the hypothesis that learning is a function of time rather than cumulative output (Lieberman, 1984; Rapping, 1965; Sheshinski, 1967). These studies have found that calendar time becomes statistically insignificant once cumulative output is included in the analysis. Related studies have attempted to distinguish between standard scale economies and the dynamic economies attributable to the learning curve (Lieberman, 1984; Stobaugh and Townsend, 1975; Preston and Keachie, 1964). The results have shown that scale economies are typically significant, but much smaller in magnitude than learning-related cost reductions. In general, the empirical evidence indicates that learning-based efficiency gains are closely linked to growth in cumulative output. Nevertheless, these efficiency gains typically stem from a wide variety of underlying sources, including improvements in capital equipment, better product and process designs, and improved organizational and individual skills.

The standard specification of the learning curve in terms of 'cumulative output' obfuscates a critical issue: is it firm-specific or total industry cumulative output that drives the learning curve? In other words, does learning remain proprietary at the firm level, or does information diffuse easily across firm boundaries so that learning is essentially an industry phenomenon? In their widely publicized work in the early 1970s, the Boston Consulting Group documented numerous learning curves based on *industry* cumulative output, but proceeded to develop strategy prescriptions on the assumption that learning was *firm-specific*. Corporate disenchantment with the outcome of learning curve-based strategies forced the Boston Consulting Group to take a second look at their data, from which they concluded that diffusion of learning was an important factor. According to their estimates, 'the real cost of most products and services declines about 25 to 30 percent each time accumulated experience doubles. However, a competitor with twice the market share characteristically has only a 5 to 10 percent cost advantage', (Boston Consulting

Group, 1978). These figures imply that roughly 60–90 percent of all learning ultimately diffuses outside the firm.<sup>2,3</sup>

Recent theoretical models (e.g. Spence, 1981) indicate that significant entry barriers can arise when learning is proprietary. The few empirical studies which have considered such entry barriers yield mixed conclusions. In a case study of the disposable diaper industry, Porter (1984) argued that such entry barriers were substantial and led to market dominance by a single firm. In a study of the chemical processing industries, Lieberman (1982) found that entry barriers were typically quite low despite the existence of steep learning curves based on industry cumulative output. As the analysis below suggests, these disparate findings are consistent if there are differences in the rate at which information diffuses across firms.

Empirical studies of industry price behavior in the presence of the learning curve indicate that prices normally decline in parallel with costs over long periods of time (Boston Consulting Group, 1972; Wiersema, 1983).<sup>4</sup> This parallel decline of prices and costs is inconsistent with most theoretical models of optimal pricing given a proprietary learning curve. However, the results below demonstrate that equilibrium prices and costs fall in parallel when there is a high rate of information diffusion across firms.

## OPTIMAL PRICING STRATEGY FOR A MONOPOLIST WITH LEARNING

Several recent studies in the marketing literature have considered the optimal pricing policy for a

<sup>2</sup> Efforts to distinguish empirically between proprietary and industry-level learning have been hampered by the fact that firm- and industry-specific measures of learning tend to be highly colinear.

<sup>3</sup> There are a wide range of channels by which information diffusion can occur. Employees may be hired-away by rival firms. Products can be examined and 'reverse-engineered'. Patents can be 'invented around' or even infringed without penalty. Consultants and contractors may disseminate information on new products and processes. Moreover, productivity improvements often stem from learning by capital equipment suppliers, whose innovations become available to all firms in the industry.

<sup>4</sup> There are, however, often periods of more rapid price reduction. These periods have been attributed to efforts to induce a 'shakeout' of less efficient firms (Boston Consulting Group, 1972) or alternatively, to new entry and the adoption of improved capital equipment by incumbent firms (Lieberman, 1984).

monopolist with learning and dynamic demand effects (Clarke, Darrough and Heineke, 1982; Kalish, 1983; Bass and Bultez, 1982; Dolan and Jeuland, 1981). Using optimal control theory, these studies demonstrate that the standard  $MR = MC$  condition for profit maximization given by static economic theory fails to be valid in a dynamic environment. This is because when a learning curve or dynamic demand effects are present, the firm's current actions affect its future costs and revenues. This inserts a 'wedge' between short-run marginal revenue and short-run marginal cost along the optimum path.

The most general formulation is provided by Clarke *et al.* (1982). They show that the following relationship holds along the optimal path:

$$MR = c + \int_t^{\infty} (c_x + qq_x/q_p)e^{-r(s-t)} ds \quad (2)$$

where  $MR$  is marginal revenue;  $c$  is short-run marginal cost;  $c_x$  is the derivative of short-run marginal cost with respect to cumulative output,  $x$ ;  $q(x,p)$  is the demand function; and  $r$  is the discount rate used by the firm. The integral in equation (2) is the 'wedge' between marginal revenue and marginal cost along the optimal path.

This integral has an intuitive interpretation. The first component,  $\int c_x e^{-r(s-t)} ds$ , corresponds to the present value of future cost savings attributable to a unit increase in output at time  $t$ . Thus, it is the 'investment value' of cost reduction resulting from an additional unit of current output. Similarly,  $\int (qq_x/q_p) e^{-r(s-t)} ds$  is the present value of the change in future revenues induced by a unit increase in output at time  $t$ . Depending on the nature of demand, additional output at time  $t$  can increase future revenues (e.g. if there are bandwagon or habit formation effects) or decrease them (e.g. if demand ultimately reaches saturation).

The optimal price path depends upon the discount rate and the nature of the learning curve and the demand function. In the absence of dynamic demand effects the monopolist's optimal price falls monotonically over time. In the extreme case where the firm's discount rate is zero, the optimal price remains constant over time and the firm always sets marginal revenue equal to its end-of-horizon marginal cost.

When there are dynamic demand effects the optimal price path is more complex. With

contagion or bandwagon effects the optimal price path may initially be increasing. Low initial prices are justified because they stimulate more rapid demand growth and hence higher revenues in later periods. With saturation in demand the optimal price path may decline toward the end of the time horizon. In certain cases the optimal price path may be discontinuous (Clarke *et al.*, 1982).

## MODELS OF COMPETITION WITH LEARNING

Several recent studies have used non-cooperative game theory to investigate the nature of competitive market equilibria when costs follow a learning curve (Spence, 1981; Fudenberg and Tirole, 1983, 1985). These studies have focused exclusively on production-side learning, ignoring the dynamic demand effects considered in the marketing literature. They have been motivated primarily by the antitrust problems which can potentially arise in industries where learning is an important factor.

In the multifirm case with output competition, the equilibrium path is defined by first-order conditions similar to those given by equation (2). In an 'open loop' or 'precommitment' equilibrium (in which firms are assumed to precommit to their entire output path in advance), the equilibrium condition for each firm  $i$  is:

$$MR_i = c_i + \int_t^{\infty} c_{x_i} e^{-r(s-t)} ds \quad (3)$$

which is identical to the monopolist's first-order condition given in equation (2), ignoring dynamic demand effects. Note, however, that a competitive firm's pricing and output decisions differ from those of a monopolist. This is because with multiple firms, marginal revenue depends upon market share.

Spence (1981) analyzed pricing and entry barriers in this open loop model in a continuous time framework assuming that firms employed a zero discount rate. Under these conditions Spence found that the learning curve could generate substantial barriers to entry. Prices in Spence's model fall with entry, but given the zero discount rate assumption, prices remain constant between entry dates. Viewing the results from an antitrust standpoint, Spence found the equilibrium number

of firms large enough to prevent serious consumer welfare loss due to monopolistic pricing, but small enough to avoid poor cost performance due to output being spread thinly across too many firms.

The ‘open loop’ equilibrium concept has the drawback that each firm is assumed to precommit to its entire output path in advance. In reality, firms may want to commit but are generally unable to do so, given the incentives to deviate from the commitment path once the game has begun. A more suitable equilibrium concept is the ‘closed loop’ equilibrium, in which firms’ output paths are optimal starting from any point in the game. The chief disadvantage of the closed loop approach is that analytical solutions are normally quite difficult to obtain. Given this difficulty, all prior learning curve studies based on closed loop equilibria have been limited to a two-period time framework.

Fudenberg and Tirole have shown that, in a closed loop equilibrium with learning, the following first-order condition holds for all firms along the equilibrium path:

$$MR_i = c_i + \int_t^\infty c_{x_i} e^{-r(s-t)} ds - \int_t^\infty p' \left( \sum_{j \neq i} \frac{\partial q^j}{\partial x_i} \right) q^i e^{-r(s-t)} ds \quad (4)$$

This is identical to the open loop formulation in (3) with the addition of a ‘strategic’ term.<sup>5</sup> This term arises because an increase in output by firm *i* at time *t* leads to a change in rivals’ outputs at time *s* > *t*. Rivals’ outputs may change for two reasons. First, an increase in experience lowers firm *i*’s cost. This increases firm *i*’s equilibrium output and *decreases* the equilibrium output of rivals. The second effect arises when learning diffuses across firms. With diffusion, an increase in experience by firm *i* reduces not only the firm’s own cost but also the costs of its rivals. This induces rivals to *increase* output in future periods.

<sup>5</sup> The strategic term,  $\int_t^\infty p' \left( \sum_{j \neq i} \frac{\partial q^j}{\partial x_i} \right) q^i e^{-r(s-t)} ds$  represents the change in firm *i*’s future revenues generated by a unit increase in current output. It is the product of (a) *p*’, the derivative of the demand curve, times (b) the total change in rival’s outputs, times (c) *q*’, the output of firm *i*, discounted over time.

### COMPUTER-AIDED SOLUTION OF MARKET EQUILIBRIA IN ‘CONTINUOUS TIME’

Given the difficulty of obtaining analytic solutions to the competitive model with learning in continuous time, a computer program was developed to solve the model numerically. The approach involved approximating the integral in equation (4) by dividing the time path into ten discrete time periods. Using this technique it was possible to solve for the market equilibrium path under a wide variety of parameter assumptions.

The basic structure of the model is as follows: industry demand is assumed to be of constant elasticity, characterized by the inverse demand function

$$q(t) = b_0 e^{gt} p(t)^{-\alpha} \quad (5)$$

where  $\alpha$  is the demand elasticity, *g* is the market growth rate,<sup>6</sup> and *b*<sub>0</sub> is the scale parameter which defines the overall market size.<sup>7</sup> With fully proprietary learning, the firm’s short-run marginal cost is assumed to be of the form

$$c_i(x_i) = c_0 x_i^{-b} \quad (6)$$

where *c*<sub>0</sub> is the cost of the first unit, *x*<sub>*i*</sub> is the accumulated output of firm *i*, and *b* is the learning ‘elasticity’ which defines the slope of the learning curve. This cost function is identical to equation (1), the conventional learning curve used in most empirical studies.

There are a number of ways in which equation (6) could be generalized to incorporate interfirm diffusion of learning. It is likely, for example, that diffusion may differ across firms (e.g. the more advanced firms may ‘leak’ more than others), and time lags in diffusion may be substantial. Ignoring these complications, we assumed the following very simple model with instantaneous diffusion:

$$c_i(x_{i,y}) = c_0 x_i^{-b(1-s)} y^{-bs} \quad (7)$$

where *y* =  $\sum x_i$  is the total industry cumulative output at time *t*, and  $0 \leq s \leq 1$  is the ‘fraction’ of each firm’s learning that diffuses into the

<sup>6</sup> Demand grows for ten periods and then drops to zero. This might be considered a crude approximation of a product life cycle. Results of the model are relatively insensitive to the exogenous growth rate, *g*.

<sup>7</sup> The product is assumed to be a non-durable good, and demand is independent of quantity consumed in prior periods.

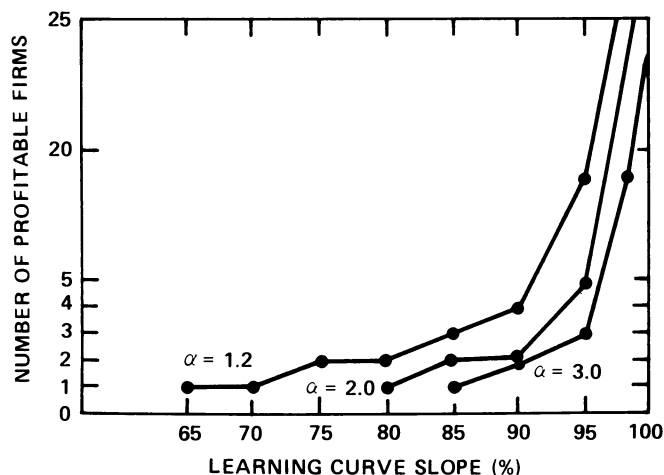


Figure 1. Number of profitable firms as a function of learning curve slope and elasticity of demand ( $\alpha$ ). Assumptions:  $b_0 = 10$ ;  $c_0 = 1.0$ ;  $g = 0.1$ ;  $r = 0$ ;  $s = 0$ ;  $T = 10$

industry common knowledge base. If  $s = 0$ , learning is entirely firm-specific; whereas if  $s = 1$ , diffusion is complete and all learning becomes public within the industry. This cost function has the advantage that the overall learning curve slope can be held approximately constant at the rate defined by  $b$ , while the parameter  $s$  can be used to vary the extent to which learning diffuses across firms.

These demand and cost functions, plus the equilibrium conditions given by (4), define the equilibrium path of price and output. Market shares are determined primarily by relative costs. The most important parameters of the model, to which attention is paid below, are the learning curve slope,  $b$ ; the extent of diffusion,  $s$ ; the firm's discount rate,  $r$ ; and the elasticity of demand,  $\alpha$ .

### ENTRY BARRIERS

The computer model was used to study the height of entry barriers as a function of the learning curve slope and the extent to which learning diffuses across firms. The results show that, with proprietary learning, entry barriers increase with the slope of the learning curve and with the elasticity of demand. This relation is illustrated in Figure 1. Entry barriers were measured by progressively increasing the number of firms allowed to enter the industry at time zero; the

figure shows the maximum number of firms that could enter profitably.

The figure indicates that with proprietary learning, entry barriers are extremely high even when the learning curve slope is in the commonly observed range between 70 and 90 percent. As the learning curve becomes steeper the equilibrium market structure reverts quickly to monopoly, especially when demand is highly elastic. However, this result is inconsistent with the empirical observation that industries with learning curves in the 70 to 90 percent range typically include more than one or two major firms (Boston Consulting Group, 1972; Lieberman, 1982).

Figure 2 illustrates the effect of diffusion of learning on barriers to entry. The results in Figure 2 are based on sequential entry; one firm per year was allowed to enter over a 10-year time horizon. The vertical scale gives the number of firms able to enter profitably. The maximum number of firms is limited to ten (i.e. one firm per year over the 10-year horizon).<sup>8</sup>

The results in Figure 2 reveal that entry barriers are substantially eroded when learning diffuses across firms. The number of entrants is positively

<sup>8</sup> Entry barriers are higher when entry is sequential rather than simultaneous. The model requires that potential entry times be specified in advance, and it assumes that these entry times are known with certainty by competitors. Firms are assumed to enter if the present value of their profits is positive.

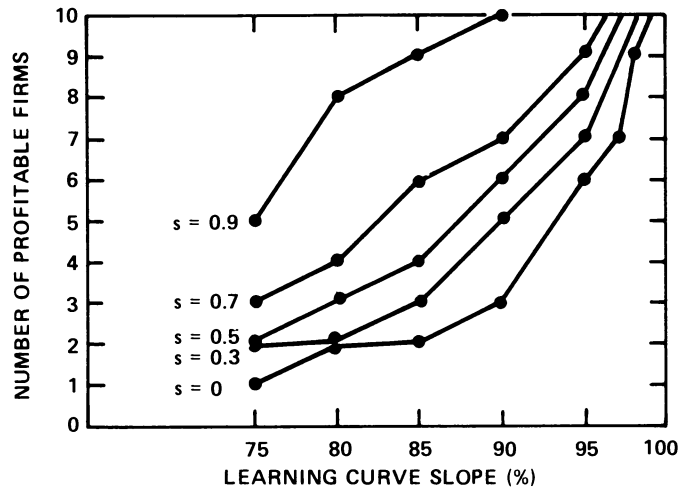


Figure 2. Number of profitable firms as a function of learning curve slope and spillover rate ( $s$ ). Assumptions: Sequential entry; one entrant per year over 10-year time horizon;  $\alpha = 1.2$ ;  $b_0 = 10$ ;  $c_0 = 1.0$ ;  $g = 0.1$ ;  $r = 0$

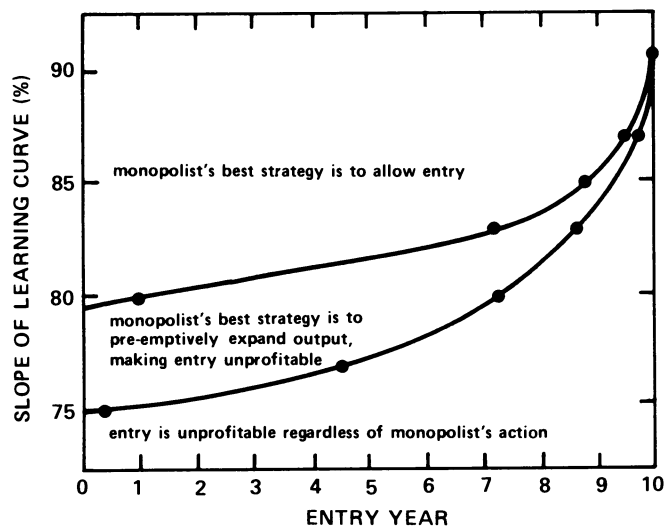


Figure 3. Profitability of entry when market held by monopolist. Assumptions:  $\alpha = 1.2$ ;  $b_0 = 10$ ;  $c_0 = 1.0$ ;  $g = 0.1$ ;  $r = 0$ ;  $s = 0$

related to the level of diffusion; with 100 percent diffusion, an unlimited number of firms can enter. Diffusion thus resolves the discrepancy between the high entry barriers documented in Figure 1 and the number of firms actually observed in most industries.

The results in Figures 1 and 2 were computed without considering the possible existence of pre-

emptive equilibria in which incumbent firms forestall entrants by producing additional output during the pre-entry period. This is akin to the aggressive behavior often advocated in strategic planning circles during the 1970s. The model reveals that such a strategy is optimal for incumbent firms only within a relatively narrow range of parameter values.

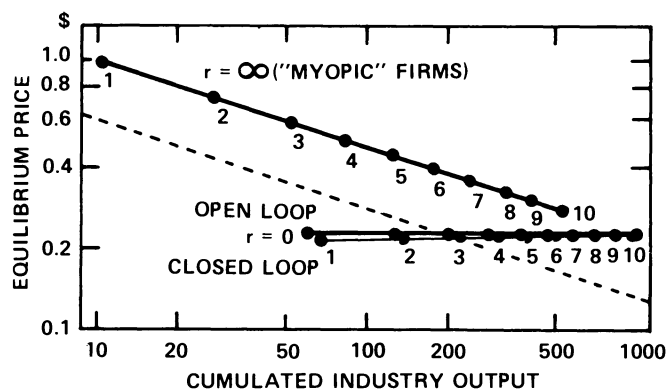


Figure 4. Path of Equilibrium Price as a Function of Firms' Discount Rate. Solid lines are equilibrium price paths; dashed line is short-run marginal cost. Assumptions: Duopoly market structure (both firms enter at time zero); learning curve slope = 80 percent; 10-year time horizon. Numbers on price curves correspond to 'year' of observation.  $\alpha = 1.2$ ;  $b_0 = 10$ ;  $c_0 = 1.0$ ;  $g = 0.1$ ;  $s = 0$

Consider, for example, Figure 3. The figure illustrates the conditions under which pre-emptive entry deterrence represents an optimal strategy for an incumbent monopolist, assuming proprietary learning and representative parameter values. In the region at the bottom of the graph, entry is unprofitable regardless of actions taken by the incumbent monopolist. Above this region is a relatively narrow band where the learning curve slope ranges between roughly 75 and 80 percent. In this band it is optimal for the monopolist to pre-empt by producing in large volume prior to the potential entry date. The additional output lowers the monopolist's marginal costs, making entry unattractive. Above this band it is not in the monopolist's interest to pre-empt, as pre-emption incurs initial losses which are not offset by later gains.<sup>9</sup>

The small size of the region in which pre-emption proves optimal in Figure 3 suggests that pre-emption is only rarely a profit-maximizing strategy in practice. Moreover, the 'optimal pre-emption region' appears considerably smaller when there are already two or more firms in the industry. Typically, incumbent firms enjoy higher profits if they follow less aggressive strategies and permit entry. This conclusion is further reinforced by the finding that the pre-emption region shrinks and eventually disappears as diffusion of learning increases.

<sup>9</sup> Note that if the monopolist deters entry by initially producing in high volume, prices are raised once the firm has lowered costs sufficiently to deter entry.

### PRICING AND PROFIT LEVELS WITH THE LEARNING CURVE AND COMPETITION

We now consider the equilibrium behavior of prices and profits in industries characterized by the learning curve. One objective is to resolve an inconsistency between the prior theoretical literature and empirical studies of price behavior. Most theoretical models (e.g. Spence, 1981) imply that, in the absence of entry, firms should hold prices constant over time (assuming a zero discount rate), or let them decline slowly (with discount rates in the normal 10 to 20 percent range). This contrasts with the empirical observation that prices tend to decline in parallel with costs over long periods of time (Boston Consulting Group, 1972). We show that equilibrium prices fall in parallel with costs when leaving diffuses across firms or when firms act myopically.<sup>10</sup> Moreover, the model reveals that profits are higher with diffusion or myopic firms.

Figure 4 illustrates the effect of firms' discount rates on the time path of prices. With a zero discount rate the optimal price path is essentially constant over time.<sup>11</sup> However, if firms are

<sup>10</sup> Prices may fall for other reasons, including demand dynamics and initial constraints on production capacity.

<sup>11</sup> In the absence of diffusion, the open and closed loop equilibria are similar. With a unitary demand elasticity the two equilibria are identical; if demand elasticity exceeds unity the closed loop price path starts below the open loop path and increases over time. See Bulow, Geanakoplos and Klemperer (1985) for a detailed discussion of the relation between demand elasticity and pricing strategy.



Table 1. Effects of Information Diffusion and Discounting on Industry Performance

Number of firms	1	1	2	2	2	2
Learning curve slope	No learning	80%	No learning	80%	80%	80%
Discount rate ( $r$ )	0	0	0	0	$\infty$	0
Diffusion rate ( $s$ )	0	0	0	0	0	1.0
Total cumulated output	20	132	90	1025	528	862
Average unit cost	1.00	0.31	1.00	0.20	0.24	0.17
Total industry profits	100	124	64	17	76	66

Assumptions:  $\alpha$ ,  $b_0$ ,  $c_0$ , and  $g$  same as Figure 4. Ten-year production period.

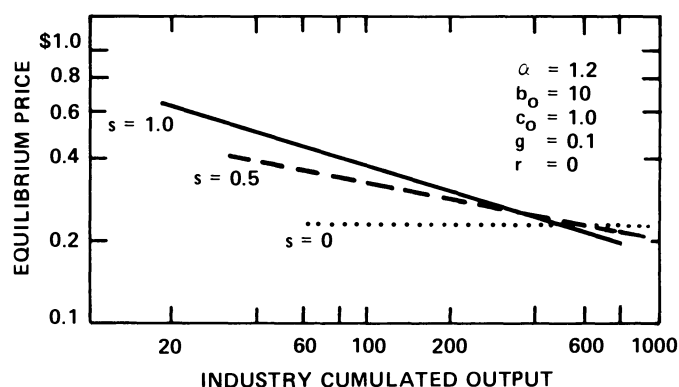


Figure 5. Effect of information on industry price. Assumptions: Same as Figure 4 with  $r = 0$

completely myopic ( $r = \infty$ ), prices decline in parallel with costs, and profit margins remain constant over time. Note that the zero and infinite discount rates represent extreme cases; if firms use a positive but finite discount rate, the equilibrium path lies between the two extremes.

One reason why firms might follow a myopic pricing strategy is that this enhances profits: Table 1 reveals that industry profits are substantially higher when firms are myopic. This is because competition is much less intense when firms behave myopically. Myopic pricing is not, however, an equilibrium strategy since firms have an individual incentive to depart from the myopic approach. Nevertheless, the myopic price may provide a convenient focal point for tacit collusion.<sup>12</sup>

<sup>12</sup> See Ghemawat (1982) on this issue. Note that *all* firms in the industry must act more or less myopically; and they remain vulnerable to new entrants who fail to adhere to the myopic pricing structure. In the model, myopic firms are normally driven out of the market by such entrants.

Table 1 documents the fact that competition is intensified by the presence of a learning curve. In the absence of diffusion, the 'investment effect' and the 'strategic effect' both provide incentives for individual firms to expand output and reduce prices. This lowers firms' profits below the level that would prevail in the absence of learning.

Figure 5 illustrates the impact of diffusion on the equilibrium path of price and output in the closed loop model. An increase in diffusion causes the price path to tilt downward until it approximately parallels the rate of cost decline.<sup>13</sup> In terms of the optimal pricing rule given by equation (4), diffusion causes the 'strategic term' to largely offset the 'investment term'. This is because additional output by the firm lowers the future costs of rivals, who are induced to expand future output and cut prices. In essence, diffusion nullifies the value of the firm's investment in cost reduction. When diffusion is complete, the

<sup>13</sup> For a more formal discussion of this relation with symmetric firms, see Ghemawat and Spence, 1985.

Table 2. Effects of diffusion and timing of entry on competitive environment

Head start of pioneer firm	Extent to which learning-based cost reductions remain proprietary	
	Fully proprietary learning (Spillover = 0)	Complete diffusion of learning (Spillover = 100%)
Long	Initial firm enjoys large lead; often highly profitable, industry less competitive.	Initial firm cannot maintain lead, and may suffer considerable losses if attempts to do so.
Short	Learning curve makes firms more aggressive in effort to gain cost advantage; often intense competition with wide range of profitability; firms with faster learning/steeper curves make higher profits.	Firms cannot gain cost advantage based on learning curve; reduces competition if correctly perceived; more evenly distributed profits.

investment and strategic terms approximately cancel.<sup>14</sup> The firm's optimal policy is then to set marginal revenue equal to short-run marginal cost, i.e. to price myopically.

Table 1 shows that under these assumptions about diffusion, output is lower than in the proprietary learning case, but costs are also lower and profits are higher. The increase in profits stems from the fact that by blunting the 'investment' incentive to expand output, diffusion induces firms to compete less aggressively.<sup>15</sup> Indeed, in some industries, firms may have an incentive to establish mutually enforceable diffusion mechanisms (e.g. patent cross-license agreements).

### IMPLICATIONS AND EXTENSIONS

The above analysis suggests that in industries where the learning curve is an important factor, the nature of competition depends critically on information diffusion. Diffusion also influences the firm's optimal strategy—aggressive pricing serves the firm's interest only if there is little diffusion, and market pre-emption can succeed only under similar conditions. In practice, how-

ever, firms often diverge from their 'optimal' strategies. For example, a firm which fails to correctly anticipate diffusion and attempts to pre-empt or expand its market share can 'ruin' the market for itself and others.

Table 2 categorizes competition into four polar extremes based on (1) the extent of diffusion and (2) the head start of the initial firm. Although the table focuses on extreme cases, it describes in a general way how the competitive environment varies with diffusion and the timing of entry.

With proprietary learning and a long head start, a pioneering firm can carve out an insurmountable cost advantage. The pioneer firm's profits are sustainable as long as there are no fundamental changes in technology. If the firm maintains a price umbrella, other less efficient firms may coexist but earn lower profits. Industries where pioneer firms have maintained major cost advantages of this sort include certain types of defense contracting, and materials processing industries such as titanium dioxide and magnesium, where the fundamental production processes can be kept proprietary. (See, for example Ghemawat, 1984, and Lieberman, 1983.)

Industries with proprietary learning but more or less simultaneous entry exhibit a wider variety of outcomes. Occasionally, a single firm can pre-empt successfully through aggressive expansion of output or greater skill at cost reduction. A more common outcome, however, is intense rivalry as firms respond simultaneously to the investment and strategic incentives which arise from the learning curve. Most cost savings are transferred to consumers, and industry profits may be low. Firms which are more skilled at

<sup>14</sup> The terms do not fully cancel unless the number of firms is very large. With complete diffusion there is no competitive incentive to gain experience, but it is in the collective interest of the industry to increase experience and cut costs. (See Stokey, 1984.)

<sup>15</sup> This, of course, requires that diffusion is correctly anticipated by firms. Firms which fail to anticipate diffusion may suffer heavy losses. This appears to have happened to many actual firms which pursued so-called 'learning curve strategies' during the 1970s.

managing the learning process earn relatively higher profits. Representative products in this category include semiconductors, digital watches, and microcomputer disk drives (*Business Week*, 1977, 1984, 1985).

If the diffusion rate is high, it is impossible for firms to acquire or maintain a significant cost advantage, even with a long head start. Firms which fail to perceive this fact and act aggressively in an effort to gain market share (following the early prescriptions of BCG), only serve to lower industry profitability for themselves and other firms. Many industries fall in this high diffusion category, where learning occurs primarily on an industry-wide basis. For example, most chemical products have these characteristics (Lieberman, 1982, 1984).

The results of the model can be extended to consider issues relating to global competition among national groups of firms which differ in their rates of (1) time discount, or (2) inter-firm diffusion. Consider, for example, a stylized global market in which American manufacturers compete with Japanese producers. If Japanese firms have lower discount rates, or lower diffusion rates, they will tend to dominate the global market even if all firms have learning curves of identical slope.

This conclusion follows from the simulation results. In the simulations, firms with low diffusion rates and/or low discount rates dominate the market equilibrium, driving out the other firms while simultaneously lowering industry profitability. This occurs because firms with lower discount rates perceive larger investment benefits associated with the learning curve, and therefore act more aggressively in their pricing and output decisions. Firms with lower diffusion rates have a similar incentive for aggressive action. With low diffusion *and* low discount rates, initial pricing below cost (i.e. 'dumping') represents an optimal strategy, even when pre-emptive or predatory behavior is ruled out.<sup>16</sup>

What might give rise to such international differences in the discount or diffusion rates of firms?<sup>17</sup> As has been argued elsewhere, managers in Japanese firms may operate with lower discount rates if their firms enjoy a lower cost of capital

or if their performance is evaluated over a relatively longer time horizon. Japanese firms may also be better able to maintain proprietary control of process improvements, given common Japanese business practices such as (1) lifetime employment for key employees, (2) heavy reliance on internally developed tooling and equipment, and (3) close supplier linkages, often maintained on an exclusive basis. Moreover, successful Japanese firms tend to operate in complex multi-stage manufacturing industries where process innovations are often organizationally embodied and widely dispersed throughout the firm, rather than codified in the form of easily transferable blueprints, formulas, and the like.

## SUMMARY AND CONCLUSIONS

This paper has presented a theoretical framework for analyzing competition in industries characterized by the learning curve. The optimal pricing rules which apply in this environment provide a guide for managerial decision-making. Moreover, they reveal the structure of the strategic problem faced by the firm. The numerical results illustrate the outcomes which arise under a variety of assumptions. The specific results on information diffusion help to resolve some major inconsistencies between prior theoretical findings and common empirical observations.

When a learning curve is present, profit maximization requires that firms set marginal revenue equal to (1) current marginal cost, plus (2) an integral which reflects the present value of future profits generated by a unit increase in current output. The components of this integral reveal the structure of the firm's strategic problem. The first component is an 'investment' term which equals the present value of the future cost savings generated by a unit increase in cumulative output. The second component is a 'strategic' term, which reflects the future response of competitors to incremental learning by the firm. (There is also an additional term which arises if dynamic demand effects are present). The 'investment' term always provides an incentive for the firm to expand output beyond the short-run profit-maximizing level. The 'strategic' term can go in either direction, depending on whether learning diffuses across firms. In the absence of diffusion, the strategic term provides an incentive

<sup>16</sup> Such pricing also maximizes social welfare, defined as the sum of consumer and producer surplus.

<sup>17</sup> Such differences between US and Japanese firms are discussed in detail in Lieberman, 1986.

to increase output. But when learning diffuses across firms, the strategic term provides an incentive to reduce output. This is because greater current output by the firm lowers the future costs of competitors, who are induced to expand future output and cut prices. In the extreme case of complete diffusion, the strategic term approximately offsets the investment term, and the optimal pricing rule approaches the static  $MR = MC$  formula of classical economic theory.

The entry barrier results highlight the importance of information diffusion. When learning is proprietary, entry barriers are exceedingly high—fewer than a handful of firms can coexist profitably when the learning curve lies in the normal 70–90 percent range. However, these entry barriers erode rapidly as diffusion of learning increases. This may explain why late entry is often feasible in industries having relatively steep learning curves.

The results also suggest that pre-emptive entry deterrence is an optimal strategy only under very limited circumstances. Deterrence is feasible only within a relatively narrow range of parameter values, and only when there is little or no diffusion. This helps to explain the disappointment of many firms with the outcomes of aggressive learning curve-based strategies pursued during the 1970s.

The results regarding the time path of prices also highlight the importance of diffusion. With proprietary learning and discount rates in the 'normal' range (i.e. less than 20 percent or so), the equilibrium price remains approximately constant over time. This is clearly inconsistent with empirical studies of actual price behavior which have shown that over long periods of time, prices tend to decline roughly in parallel with costs. Diffusion of learning provides one very plausible resolution of this discrepancy. With diffusion, equilibrium market prices fall in parallel with production costs. Diffusion also reduces competitive rivalry, thereby enhancing firms' profits.

A second case in which prices parallel costs (and profits are enhanced) is when firms have high discount rates, or for other reasons act myopically. Myopic firms ignore the investment and strategic implications of the learning curve. Myopic behavior may be rational if there is considerable uncertainty regarding future demand conditions or the likelihood of continued cost

reduced. Myopic behavior also proves rational if there is a high rate of information diffusion.

From the standpoint of strategic planning, the findings underscore the danger of simple strategy prescriptions based on the learning curve. The existence of a learning curve gives rise to incentives which often intensify competition and reduce profits. Only rarely is it in firms' interests to pursue 'pre-emptive' strategies. And although often overlooked, information diffusion plays a key role in the competitive process. In the past, strategic planners have tended to emphasize the slope of the learning curve. It is perhaps more important to consider the extent to which learning occurs internally within a firm (rather than coming from outside sources) and the degree to which such internally generated learning can be kept proprietary for an extended period of time.

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