A Behavioral Analysis of Learning Curve Strategy

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Introduction

Learning curves have been identified in a wide variety of industries (Dutton and Thomas, 1984), and an extensive theoretical literature has explored their strategic implications. A learning curve creates a positive feedback loop by which a small initial market share advantage leads to greater production experience, lower unit costs, lower prices and still greater market share advantage. In general, the literature suggests that in the presence of learning curves – and when learning is privately appropriable – firms should pursue an aggressive strategy in which they seek to preempt their rivals, expand output and reduce price below the short-run profit maximizing level (Spence, 1981; Fudenberg and Tirole, 1983, 1986; Tirole, 1990). Intuitively, such aggressive strategies are superior because they increase both industry demand and the aggressive firm's share of that demand, boosting cumulative volume, reducing future costs and building sustained competitive advantage until the firm dominates the market. The desirability of aggressive strategies in industries with learning curves has diffused widely in business education, the popular business literature, management texts, and public policy debates (Rothschild 1990, Hax and Majluf, 1984; Oster, 1990; Porter, 1980; Krugman, 1990), and learning curve strategies appear to have led to sustained advantage in industries such as synthetic fibers, bulk chemicals and disposable diapers (Shaw and Shaw 1984; Lieberman 1984, Ghemawat 1984, Porter 1984). However in many industries, including televisions, VCRs, semiconductors, toys and games, lighting equipment, snowmobiles, hand calculators, tennis equipment, bicycles, chain saws, running shoes and vacuum cleaners, aggressive pricing and capacity expansion have led to substantial overcapacity and price wars that have destroyed industry profitability (Beinhocker, 1991; Salter, 1969; Porter, 1980; Saporito, 1992; The Economist, 1991; Business Week, 1992).

Existing models that consider the competitive implications of the learning curve utilize the traditional assumption that markets clear at all points in time. Market clearing in turn implies that a firm's production capacity and other resources can be adjusted instantaneously to equilibrium levels, or, if there are capacity adjustment lags, that firms have perfect foresight such that they can forecast their capacity requirements far enough in advance to bring the required capacity on line just as it is needed. Neither assumption is valid: it takes time to build new factories, expand existing ones, and decommission obsolete ones (Mayer 1960, Jorgenson and Stephenson 1967), and forecasting over typical planning horizons remains difficult and error-prone (Armstrong 1985, Makridakis et al. 1982, Makridakis et al. 1993). The presumption in the literature is that capacity adjustment and forecast error correction are fast relative to the dynamics of the learning curve so that the assumption of perfect market clearing is a reasonable approximation.

In this paper we show that relaxing the assumptions of instantaneous market clearing and perfect foresight leads, in a variety of plausible circumstances, to competitive dynamics significantly different from those predicted by much of the existing literature.

A Boundedly Rational, Disequilibrium Model

To explore the robustness of the learning curve literature to the assumptions of perfect foresight and instantaneous market clearing, we developed a disequilibrium, behavioral model of competitive dynamics in the presence of learning. Following Kalish (1983), we assume that the market goes through a life-cycle of growth, peak, and saturation. In contrast to the literature, we assume capacity adjusts with a lag, and that firms have only a limited ability to forecast future sales. These assumptions are consistent with a long tradition of experimental and empirical evidence (Brehmer 1992, Collopy and Armstrong 1992, Diehl and Sterman 1995, Kampmann 1992, Mahajan et al. 1990, Paich and Sterman 1993, Parker 1994, Rao 1985, Sterman 1989a, 1989b, 1994). In models assuming instantaneous market clearing and perfect foresight, the market clearing price can be derived as a necessary property of equilibrium, given the capacity decision. However in disequilibrium settings, both price and capacity targets must be determined. Here we draw on the literature cited above and the well-established tradition of boundedly rational models, and assume that firms set prices with intendedly rational decision heuristics (Cyert and March, 1963/1992; Forrester 1961; Simon 1976, 1979, 1982; Morecroft 1985).

The model is formulated in continuous time as a set of nonlinear differential equations. Since no analytic solution to the model is known, we use simulation to explore its dynamics. While the model portrays an industry with an arbitrary number of firms, we restrict ourselves to the duopoly case in the simulations here. The equations and parameters are presented below.

Results

We first run the model under the assumption that capacity can be adjusted instantly and costlessly to the equilibrium level (that is, equation 23 is replaced by $K = Q^*/ u^*$). This case tests the ability of the model to replicate the results of the neoclassical models. Figure 1 shows the behavior of the model for several industry demand growth scenarios, assuming perfect capacity adjustment. The scenarios ranges from slow and steady market growth to a vigorous boom followed by a significant bust when the market saturates; the scenarios are within the range of experience observed for a wide range of products.

We next consider the payoff structure in the 2-player game where firm strategies may be either aggressive or conservative. The aggressive player sets a market share goal of 80% and will opportunistically seek more if it detects additional undercapacity in the industry; the conservative player sets a market share goal of 50% and will cede additional share if it detects industry overcapacity is likely (see equations). Consistent with the neoclassical literature, the learning curve creates a strong strategic incentive for firms to play aggressively and preempt their competitor, defining a prisoner's dilemma (Table 1). As shown in Figure 2 the payoff structure is not affected by the speed of the market dynamics. Each player continues to have a strategic incentive to aggressively expand capacity and price low even when industry demand goes through a strong boom followed by a sudden and severe collapse – a direct consequence of the fact that perfect and instantaneous capacity adjustment implies capacity always is exactly at the optimal level no matter how volatile the demand.

Table 1. Payoffs for the perfect capacity case in three industry evolution scenarios (NPV of cumulative profits, Billion $). The payoffs form a prisoner's dilemma in all three cases: firms always have an incentive to defect from the [C, C] case; a firm finding itself playing conservative when its rival plays aggressive will do better by also playing aggressive.

SLOW (β=.5)		Aggressive	Conservative
	A	3.2, 3.2	5.1, 2.1
	C	2.1, 5.1	3.8, 3.8

MEDIUM (β=1)		Aggressive	Conservative
	A	4.8, 4.8	7.3, 3.2
	C	3.2, 7.3	5.7, 5.7

FAST (β=2)		Aggressive	Conservative
	A	6.5, 6.5	9.4, 4.8
	C	4.8, 9.4	7.6, 7.6

Figure 1. Diffusion dynamics for three values of the word of mouth parameter, β (Slow, Medium, Fast: β = .5, 1, 2 respectively), for the perfect capacity case with target market share for both firms = 50%. Top to bottom: Adopters, Industry Order Rate, Price.

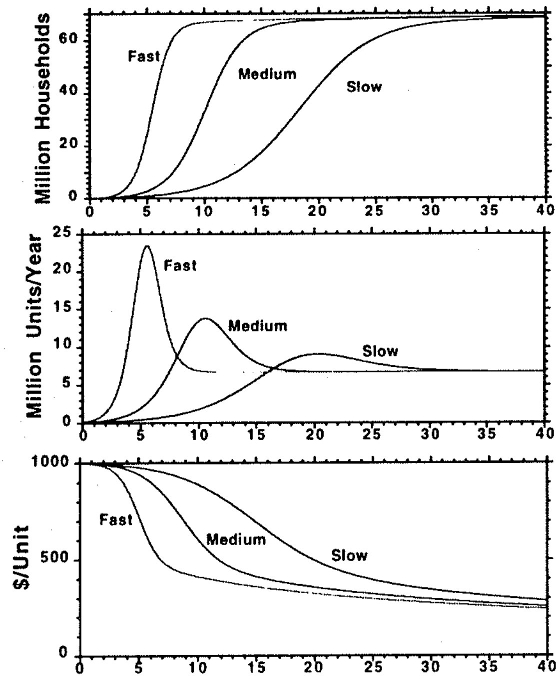
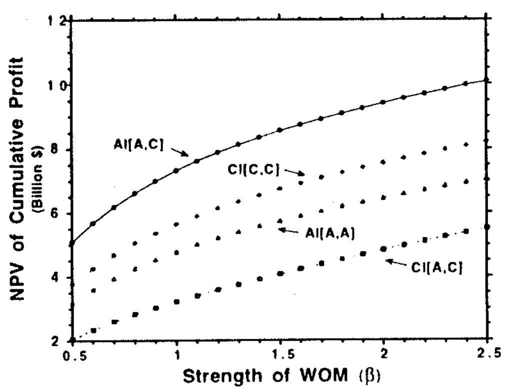


Figure 2. Firm Payoffs as they depend on the speed of the product lifecycle, perfect capacity case. Firms always have a strategic incentive to preempt and play the aggressive strategy.



We now relax the assumption of perfect market clearing by assuming capacity adjusts to the target level with a one year third-order delay, as specified in the equations below. Capacity needs are based on a forecast of industry demand, which in turn is determined by extrapolation of recent growth trends in industry orders. The forecasting procedure is well documented in both the empirical and experimental literature.

As seen in Table 2, the lag has little effect on the payoff structure when market demand evolves slowly: the payoffs still form a prisoner's dilemma. But when the market dynamics are fast, leading to rapid growth and a sudden transition to saturation, the payoffs reverse, and the aggressive player is dominated by the conservative firm: playing conservative becomes the Nash equilibrium. As seen in figure 3, above a critical value of the word of mouth parameter which defines how fast demand grows, the aggressive strategy becomes inferior. Figure 4 shows that the cause of the shift is the overshoot of capacity caused by the interaction of forecast error with the capacity adjustment delay. The learning curve still favors the aggressive firm, giving the aggressor an even larger cost advantage compared to the conservative firm than in the perfect capacity case. However, the cost advantage conferred by the learning curve is overwhelmed by the large losses incurred during the market bust, when the aggressor's capacity overshoots demand, leaving the aggressive firm with high fixed costs and large losses.

Table 2. Payoffs for the capacity adjustment lag case in three industry evolution scenarios (NPV of cumulative profits, Billion $).

SLOW (β=.5)		**Aggressive**	**Conservative**
	A	-7.0, -7.0	4.8, 0.9
	C	0.9, 4.8	3.5, 3.5

MEDIUM (β=1)		**Aggressive**	**Conservative**
	A	-11.1, -11.1	5.2, 1.0
	C	1.0, 5.2	4.4, 4.4

FAST (β=2)		**Aggressive**	**Conservative**
	A	-19.7, -19.7	-1.7, 0.2
	C	0.2, -1.7	1.9, 1.9

Figure 3. Firm Payoffs as they depend on the speed of the product lifecycle when capacity adjusts with a one-year lag. The aggressive strategy is inferior for $\beta > \beta^{CRIT}$. Compare to fig. 2.

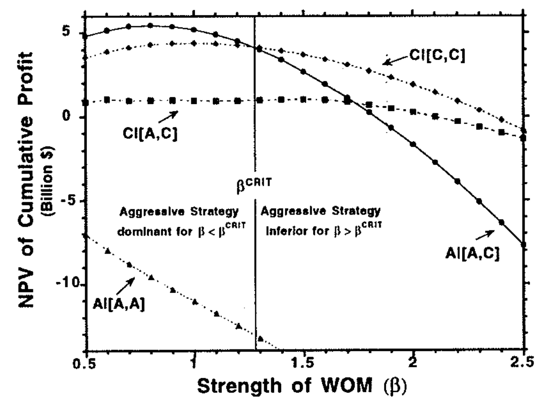
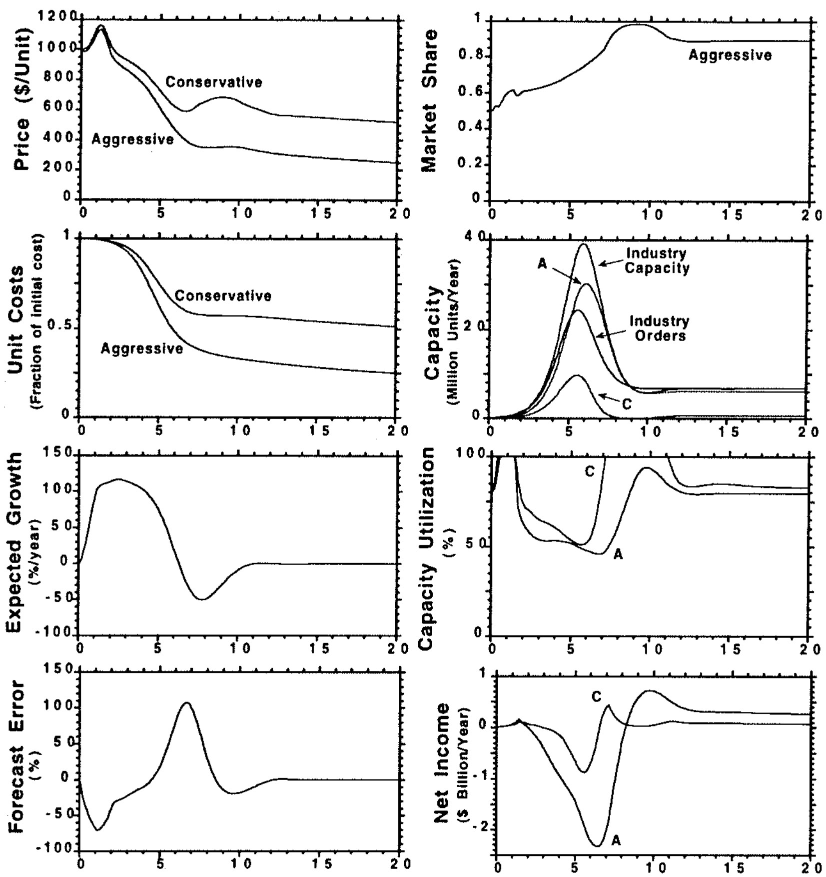


Figure 4. Dynamics of the aggressive vs. conservative strategies in the fast market scenario ($\beta = 2$), with the capacity acquisition lag.



Discussion

Prior research has shown that under assumptions of equilibrium and perfect rationality, the optimal strategy for a firm facing a learning curve is to aggressively preempt competitors, cutting price and boosting output beyond the static optimum levels. We have shown that under a more realistic set of assumptions, the normative result can be reversed. When there are capacity adjustment lags, commonly used forecasting heuristics lead to capacity overshoot as a market saturates. Investing in additional capacity and lower prices to achieve learning benefits is only optimal when the dynamic complexity of the market, and hence the risk of capacity overshoot, is low. In these circumstances fully and boundedly rational decision making converge. However, as the dynamic complexity of the market increases, disequilibrium effects and systematic decision making errors become more important, and cause the predictions of the rational model to fail.

These conclusions are consistent with experimental and empirical evidence. The results predict that learning curve strategies will perform best in industries where there is slow demand growth (or where customer awareness of the product category is already high), the product has a high repeat purchase rate and is fairly undifferentiated, or where capacity can be adjusted rapidly at low cost. Observations that learning curve strategies generally led to sustained advantage in industries such as synthetic fibers, bulk chemicals, and disposable diapers are broadly consistent with this prediction. Similarly, our results predict poor performance for aggressive strategies in industries with high word of mouth, durable, differentiated products, or long capacity adjustment delays. The overcapacity and price wars observed in industries such as televisions and VCRs, toys and games, lighting equipment, snowmobiles, hand calculators, tennis equipment, bicycles, chain saws, semiconductors, and running shoes cited earlier support this proposition.

The results have implications both for practicing managers and for the larger issue of the modeling tools most appropriate for the study of strategic behavior. The recommendation to pursue a learning curve strategy must always be treated with caution. Current texts and theory suggest firms should assess the strength and appropriability of learning curves in their industry and recommend aggressive preemption in the presence of strong, appropriable learning curves or other positive feedbacks that confer increasing returns. Our results show that firms must also determine whether they are vulnerable to capacity overshoot or underestimation of competitor capacity plans. A firm electing to pursue a learning curve driven strategy must devote significant effort to understanding the dynamics of market demand so that it is not caught unprepared by market saturation. It must clearly and credibly signal its capacity intentions in a rapidly growing market so that less aggressive players will not unintentionally overbuild. To prevent competitor overbuilding, it may find it optimal to share its forecasts and market intelligence with rivals. Experience and experimental studies suggest that this is both hard medicine to take and difficult to carry out successfully. Rather, it appears that when high dynamic complexity increases the risk of capacity overshoot, firms should consider conservative strategies even in the presence of learning curves and other sources of increasing returns, allowing less sensible rivals to play the aggressive strategy, then buying these rivals at distress prices when they fail during the transition from boom to bust. Jack Tramiel followed just such a strategy, purchasing Atari from Warner Communications after the peak in the video game market for $160 million in unsecured debt and no cash, while Warner took a $592 million writeoff of Atari assets on top of $532 million in Atari losses.

On the methodological front, our results suggest that the equilibrium and rationality assumptions of game theory and microeconomics are not robust. More realistic physical, institutional and behavioral assumptions can reverse the neoclassical result and reveal a much more complex relation between the learning curve, the dynamics of demand and firm strategy.

When the system dynamics are sufficiently slow, the delays in information acquisition, decision making and system response sufficiently short, and the cognitive demands on the agents sufficiently low, behavioral theories will yield predictions observationally indistinguishable from those of equilibrium models. However, in cases of high dynamic complexity, boundedly rational people can and do behave significantly differently. The case of the learning curve in a dynamic market shows these differences can matter greatly, and their impact can be examined rigorously. We speculate that relaxing the assumptions of rationality and equilibrium may lead to similar differences in a variety of other contexts. Such cases are likely to include settings in which there are long time delays between action and effect or in the reporting of information, where there are positive feedback processes (increasing returns), and where there are significant nonlinearities (Sterman 1994, Arthur 1994). Likely examples include markets such as shipbuilding, real estate, paper, and many others plagued by chronic cyclicality, and industries with network externalities and standard formation issues such as telecommunications and software. We suggest the combination of game theoretic reasoning with behavioral simulation models can help create a meaningful 'behavioral game theory' (Camerer 1990, 1991), that is, a behaviorally grounded, empirically testable, and normatively useful theory of disequilibrium dynamics in strategic settings.

Model Equations

Industry Demand

$Q^O = Q^I + Q^R$.	*Industry Orders*	(1)
$Q^I = \mu(dM/dt)$.	*Initial Industry Orders*	(2)
$dM/dt = N(\alpha + \beta M/POP)$	*Adopters*	(3)
$N = MAX(0, M^* - M)$	*Potential Adopters*	(4)
$M^* = MAX(0, MIN(POP, POP^r + \sigma(P^{min} - P^r)))$	*Equilibrium adopter population*	(5)
$Q^R = \Sigma_i D_i$.	*Replacement Purchases*	(6)
$D_i = \delta I_i$	*Discards*	(7)
$I_i = \int(Q_i - D_i)dt + I_{i0}$.	*Installed base of product*	(8)
$O_i = S^O_i \cdot Q^O$	*Orders to firm i*	(9)
$S^o_i = A_i/\Sigma_j A_j$	*Share of orders to firm i*	(10)
$A_i = [EXP(\varepsilon_p P_i/P^r)][EXP(\varepsilon_a(B_i/Q_i)/\tau^r))$	*Attractiveness of firm i*	(11)

The Firm *(subscripts for firm i omitted for clarity)*

$\pi = R - (C_f + C_v)$.	*Profit of firm i*	(12)
$R = Q(V/B)$.	*Revenue*	(13)
$V = \int(P \cdot O - R)dt + V_0$.	*Value of order book*	(14)
$C_f = U_f \cdot K$	*Fixed Costs*	(15)
$C_v = U_v \cdot Q$	*Variable Costs*	(16)
$U_f = U_{f0} \cdot (E/E_0)^\gamma$	*Unit Fixed Costs*	(17)
$U_v = U_{v0} \cdot (E/E_0)^\gamma$	*Unit Variable Costs*	(18)
$E = \int Q dt + E_0$	*Cumulative Experience*	(19)
$Q = MIN(Q^*, K)$.	*Production (= Shipments)*	(20)
$Q^* = B/\tau^*$	*Desired Production*	(21)
$B = \int(O - Q)dt + B_0$	*Backlog of unfilled orders*	(22)
$K = \mathcal{L}(K^*, \lambda)$	*Capacity (3rd order delay of K*)*	(23)

Firm Strategy

$K^* = MAX[K^{min}, S^* D^e/u^*]$	*Target Capacity*	(24)
$D^e = D^r EXP(\lambda^f g^e)$	*Expected Industry Demand*	(25)
$d(D^r)/dt = (Q^O - D^r)/\tau^d$	*Reported Industry Order Rate*	(26)
$g^e = \ln(D^r_t / D^r_{t-\lambda^h})/\lambda^h$	*Expected industry demand growth rate*	(27)
$S^* = \begin{cases} MAX(S^{min}, S^u) & \text{if Strategy = Aggressive} \\ MIN(S^{max}, S^u) & \text{if Strategy = Conservative} \end{cases}$	*Target Market Share*	(28)
$S^u = MAX(0, D^u/D^e)$.	*Uncontested Market Share*	(29)
$D^u = D^e - u^* \Sigma_j K^c_j, \quad j \neq i$.	*Uncontested Industry Demand*	(30)
$d(K^c_j)/dt = (K^*_j - K^c_j)/\tau^c$.	*Expected Competitor Capacity*	(31)
$dP/dt = (P^* - P)/\tau^p$	*Price*	(32)
$P^* = MAX\{U_v, P[(1+\alpha^c((P^c/P)-1))(1+\alpha^d((Q^*/(u^* K))-1))(1+\alpha^s(S^*-S))]\}, \quad \alpha^c \geq 0; \alpha^d \geq 0; \alpha^s \leq 0$	*Indicated Price*	(33)
$P^c = (1 + m^*)(U_v + U_f)$.	*Indicated Price from Cost*	(34)

Parameters and initial conditions.

n	number of firms in industry	2
μ	Average number of units per household (units/household)	1
α	Propensity for nonadopters to adopt the product autonomously (1/years)	.001
β	Propensity for nonadopters to adopt the product through word of mouth (1/years)	1
POP	Total population (households)	100e6
σ	Slope of the demand curve (Households/($/unit))	$-.2(POP^*/P^*)$
POP^r	Population that would adopt at the reference price P^r (households)	60e6
P^r	Price at which industry demand equals the reference population POP^r ($/unit)	1000
δ	Fractional discard rate of units from the installed base (1/years)	.10
ε_p	Sensitivity of product attractiveness to price	-8
ε_a	Sensitivity of product attractiveness to availability	-4
U_{v0}	Initial unit variable cost ($/unit)	$(P_{i0}/(1+m^*))/(1+c)$
U_{f0}	Initial unit fixed cost ($/unit)	$c(P_{i0}/(1+m^*))u^*/(1+c)$
c	Ratio of fixed to variable costs (dimensionless)	3
γ	Strength of the learning curve (dimensionless)	$\log_2(.7)$
τ^*, τ^r	Target delivery delay, reference delivery delay (years)	.25
λ	Capacity acquisition delay (years)	1
u^*	Target capacity utilization rate (dimensionless)	.8
K^{min}	Minimum efficient scale (units/year)	1e5
λ^f	Forecast horizon (years)	λ
τ^d	Time delay for reporting industry order rate (years)	.25
λ^h	Historic horizon for estimating trend in demand (years)	1
τ^c	Time delay for estimating competitor target capacity (years)	.25
τ^p	Adjustment time for price (years)	.25
α^c	Weight on costs in determination of target price (dimensionless)	1
α^d	Weight on demand/supply balance in determination of target price (dimensionless)	.5
α^s	Weight on market share in determination of target price (dimensionless)	-.10
m^*	Target profit margin (dimensionless)	.2
S^{min}, S^{max}	Market share targets for aggressive and conservative strategies	.8, .5
M_0	Initial number of adopters (households)	$.001M^*$
I_{i0}	Initial installed base of product for firm i (units)	$.5\mu M$
V_{i0}	Initial value of order backlog of firm i ($)	$P_i \cdot B_{i0}$
B_{i0}	Initial order backlog of firm i (units)	$.5Q^O\tau^*$
E_{i0}	Initial cumulative production experience of firm i (units)	10e6
K_{i0}	Initial capacity of firm i (units/year)	K^*_{i0}
K^c_j	Initial estimate of competitor j's target capacity (units/year)	K^*_j
D^r_{i0}	Initial value of reported industry demand (units/year)	Q^O
P_{i0}	Initial price of firm i ($/unit)	1000