A Theory of Market Structure with Sequential Entry

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and

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This article sets out a theory of market structure with sequential entry. We characterize the perfect Nash equilibrium to the entry game in several propositions. First, equilibria never involve excess capacity. Second, a sufficient statistic for the entry of any firm is that its profits are positive when computed myopically, i.e., with no further entry. Third, the equilibrium number of firms is the smallest number that can deter entry. Fourth, aggregate output in equilibrium is no smaller than the limit output. We calculate some explicit solutions to the model and examine comparative static properties.

1. Introduction

■ Beginning with the limit-pricing models of Bain (1956), Modigliani (1958), and Sylos-Labini (1962), the modern theory of strategic entry deterrence has grown increasingly sophisticated, but has not achieved its purpose (at least as intended by Bain): the endogenization of market structure. Although today's students of industrial organization are told that conduct feeds back on to structure, and that the two are determined simultaneously, there are few, if any, formal models describing how this determination occurs. The early models of limit pricing cited above restricted attention to a monopolist incumbent's (or collusive oligopoly's) trying to deter a single entrant. This one incumbent-one entrant framework has dominated the theoretical literature. Recent work within this framework has concentrated on refining the concept of strategic investment to deter entry, for example, by the introduction of the concept of perfectness, or credibility into the entry game (Dixit, 1980; Eaton and Lipsey, 1981; Spence, 1977; Fudenberg and Tirole, 1983; Gilbert, 1986; Ware, 1984). Gilbert (1986) provides an enlightening synthesis of this literature. The next step on the theoretical agenda is to use this strategic framework to develop a model in which tastes and technology, but not market structure, are exogenous.

   This article accomplishes that task for a restrictive, but not uninteresting, set of demand and cost conditions. The number of firms, aggregate output, and the size distribution of producing firms are determined as the solution to a sequential entry game of perfect information. Although firms enter in sequence, all firms have perfect foresight about the pattern

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of future entry and the equilibrium price (the equilibrium is subgame perfect). The equilibrium is entry deterring in that the next firm in sequence after the last successful entrant cannot enter and earn positive profits.

Some attempts have been made to extend the modern theory of entry deterrence beyond the one incumbent-one entrant framework. An early and important article that pioneered the ideas of sequential entry and endogenous market structure is Prescott and Visscher (1977). Bernheim (1984) considers a sequence of potential entrants and shows that making entry conditions easier may, perversely, lower the scope for entry, because any potential entrant anticipates greater subsequent entry, and hence lower available rents in the final equilibrium. Gilbert and Vives (1984) examine a model with several incumbents and entrants, in which firms incur a sunk entry fee but no sunk production costs. Incumbents move simultaneously in making strategic production decisions toward a sequence of potential entrants. McLean and Riordan (1985), in a paper with a motivation similar to ours, consider the perfect equilibrium to a sequential entry game in which firms choose irreversibly a production technology at the time of entry, and market structure is determined endogenously.

We have been careful to match the strategic structure of the game to the technology, in a way that many previous articles in the area have failed to do. The strategic advantage of earlier movers is conferred only by sunk investments; the later movers use the same technology and are able, in fact obliged, to make sunk investments in the same way to enter the industry. Thus, games of this type are properly modelled in two phases—first, a phase in which all strategic (sunk) investments are committed, and second, a production phase that is nonstrategic and in which a quantity equilibrium (in our case Cournot) is realized, conditioned on the vector of strategic investments made in phase one. The recognition that later movers also incur sunk investment costs gives the earlier movers less strategic power than in models in which this point is ignored. Ware (1984) discusses the distinction in detail for a one incumbent-one entrant model. Our article can be viewed as an extension of the framework developed there to the case in which the number of potential firms is large.

In Section 2 we present our model and develop some useful propositions characterizing the quantity equilibrium, given any vector of strategic investments. In Section 3 we develop three propositions that characterize the perfect Nash equilibrium of the sequential entry game. First, equilibrium never involves excess capacity. Second, a necessary and sufficient statistic for entry of any firm is that its maximal profit, computed on the assumption of no further entry, be positive. As a corollary, aggregate output is no smaller than the limit output. Finally, the equilibrium number of firms is the smallest number that can deter further entry.

In Section 4 we present and discuss some simulation results. Using a computer algorithm, we are able to vary parameters of the model, such as the degree to which the technology is sunk, and to analyze the effect on the equilibrium configuration of firms. This allows us to assess the impact of strategic behavior on the industry. Perhaps surprisingly, we find that strategic entry deterrence is ordinarily welfare improving in our model, because equilibrium output does not change significantly, but the number of firms, and hence the sunk costs associated with entry, are reduced.

The reason for the relative constancy of equilibrium output is that a form of limit pricing is embodied in the entry-deterring equilibrium. It has been clear that limit pricing behavior might work to the benefit of consumers since the work of Bain. In expanding capacity and output to deter entry, a monopolist will lower price and reduce the social cost of monopoly. In our model there is an additional benefit to entry-deterring behavior: a shift in the equilibrium market structure toward the efficient structure, which with globally increasing returns is just a single firm.

Curiously, we discover that the equilibrium profit of firms is not monotonically decreasing in the order of entry: the privilege of being an early entrant is not necessarily valuable. In Section 5 we briefly comment on the possible significance of our results.

2. The model

■ We begin by making four assumptions.

Assumption 1. All firms produce an undifferentiated product with inverse demand function $p = f(\tilde{X})$, where $\tilde{X}$ is aggregate output.

Assumption 2. The function $f(\tilde{X})$ is twice differentiable, and, for $f(\tilde{X}) > 0$, $f'(\tilde{X}) < 0$. Further, $f'(\tilde{X}) + \tilde{x}_i f''(\tilde{X}) < 0$, for all $\tilde{x}_i \leq \tilde{X}$, where $\tilde{x}_i$ is output of firm i.

The second restriction in Assumption 2 is that the marginal revenue of any firm is decreasing in any other firm's output. As we observe below, this property is crucial for the results we obtain, and the assumption is therefore not innocuous.[1]
    There are n potential firms.

Assumption 3. For any firm i the cost function is $C(\tilde{x}_i, k_i) = F(k_i) + V\tilde{x}_i$, $\tilde{x}_i \leq k_i$.

$F(k_i)$ is the cost of capacity k_i. We suppose that, once incurred, capacity costs are sunk. Output can be produced at constant variable cost V per unit, up to capacity k_i. We further assume the following.

Assumption 4. $F(0) = 0$; $F(k_i) > 0$, for $k_i > 0$; $F(k_i) > F(k_0)$, for $k_i > k_0$; and $F(k_i)/k_i < F(k_0)/k_0$, for $k_i > k_0$.

Notice that capacity costs are increasing in k_i, but average capacity costs are decreasing in k_i.[2]
    We analyze an $(n + 1)$-stage game of perfect information (Kuhn, 1954) in which firms 1 through n sequentially choose capacities $k^n = (k_1, \ldots, k_n)$ in the first n stages. In the $(n + 1)$st stage, they play a capacity-constrained Cournot game in quantities. An equilibrium to a game of perfect information is, of course, subgame perfect in the sense of Selten (1975).

□ **Properties of the constrained Cournot equilibrium.** Given $k^n = (k_1, k_2, \ldots, k_n)$, the quantity equilibrium, which we denote by $x^n = (x_1, x_2, \ldots, x_n)$, is the solution to

$$x_i = \min(k_i, Z(X_{-i})), \qquad i = 1, \ldots, n,$$

where $X_{-i} = \sum_{j \neq i} x_j$ and $Z(X_{-i})$ is $\operatorname*{argmax}_{x_i} x_i f(X_{-i} + x_i) - Vx_i$. That is, $Z(\cdot)$ is the Cournot reaction function for the quantity-setting game in stage $(n + 1)$. Notice that the symbols x_i and X refer to Cournot *equilibrium* quantities, given capacities.
    In Figure 1 we illustrate the solution to the quantity game where there are two firms, one and two, with positive capacities in stage $(n + 1)$. There are four regions in the figure: in I, both firms are unconstrained by their capacities; in II both are constrained; in III (IV), one (two) is constrained and two (one) is unconstrained. The boundary between regions II and IV is $Z(x_2)$ and the boundary between II and III is $Z(x_1)$.
    In the Cournot equilibrium there are potentially three types of firms, which are described in the following definition.

Definition 1. If $x_i < Z(X_{-i})$, firm i is *constrained*. If $x_i = Z(X_{-i})$, firm i is: (a) *semiconstrained* if $x_i = k_i$; (b) *unconstrained* if $x_i < k_i$.

Notice that the output of any firm which is either constrained or semiconstrained is equal to its capacity ($x_i = k_i$), and that the output of an unconstrained firm is less than its capacity.

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[1] A defense of this assumption that has been cited commonly by other authors is that it is sufficient for stability of a Cournot equilibrium.
[2] This seems to be a reasonable simplification of observed cost functions in many manufacturing industries.

FIGURE 1

THE FOUR PHASES OF CONSTRAINED COURNOT EQUILIBRIUM FOR DUOPOLY
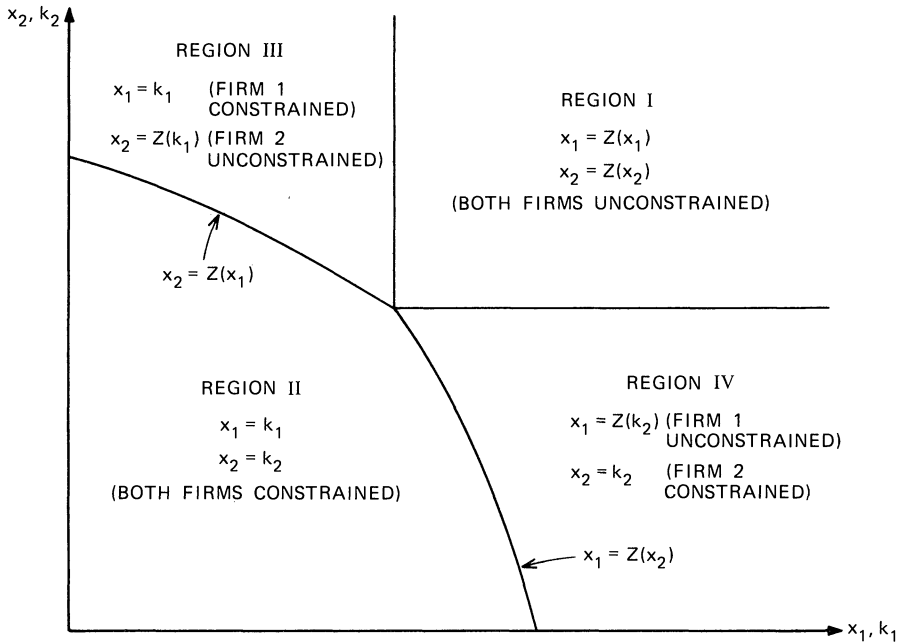
To analyze the sequential entry game we need some properties of the Cournot equilibrium, which are summarized in the following four propositions.

Proposition 1. Given $k^n = (k_1, \ldots, k_n)$, the Cournot equilibrium $x^n = (x_1, \ldots, x_n)$ is unique.

The proof of uniqueness is a direct application of the Rosen (1965) uniqueness theorem. The theorem requires that the game is strictly smooth (Friedman, 1986, p. 44); second, that the Jacobian of the system of first-order conditions, which will not be simultaneously satisfied at boundary equilibria, be negative quasi-definite (Friedman, 1986, p. 45).

Proposition 2. (a) x_i and X ($=\Sigma \ x_i$) are continuous in k^n. (b) Given $(k_1, \ldots, k_{i-1}, k_{i+1}, \ldots, k_n)$, there exists a $\hat{k}_i > 0$ such that firm i is constrained if $k_i < \hat{k}_i$, semiconstrained if $k_i = \hat{k}_i$, and unconstrained if $k_i > \hat{k}_i$. (c) If firms i and j are either semiconstrained or unconstrained, then $x_i = x_j$. (d) If firm i is constrained and firm j is either semiconstrained or unconstrained, then $x_i < x_j$. (e) x_i is decreasing in k_j if i is unconstrained and j is constrained, and nonincreasing otherwise. (f) x_i and X are increasing in k_i if i is constrained, and nondecreasing otherwise.

Proofs of parts (a), (b), (c), and (d) are trivial. Proofs of parts (e) and (f) are straightforward but tedious, and have been omitted for the sake of brevity.

Definition 2. Let $H_i(k^n) = x_i f(X) - Vx_i$ denote the *gross profit* of firm i in Cournot equilibrium.

Proposition 2 has immediate consequences for these gross profit functions that we record in Proposition 3.

Proposition 3. (a) $H_i(\cdot)$ is continuous in k^n. (b) $H_i(\cdot)$ is decreasing in k_j, $j \neq i$, if j is constrained. (c) For any $k_i > 0$, $\bar{k}_j = 0$, and $\tilde{k}_j > 0$, $H_i(k_1, \ldots, \bar{k}_j, \ldots, k_n)$ $> H_i(k_1, \ldots, \tilde{k}_j, \ldots, k_n)$, $j \neq i$. (d) For any pair $\bar{k}_j$, $\tilde{k}_j$ such that j is either semiconstrained or unconstrained, $H_i(k_1, \ldots, \bar{k}_j, \ldots, k_n) = H_i(k_1, \ldots, \tilde{k}_j, \ldots, k_n)$ for all i.

There are some immediate and useful implications of Propositions 2 and 3 concerning the effect of adding or subtracting firms, which we loosely call the entry and exit corollaries.

Entry Corollary. Suppose initially that m firms, $m < n$, have positive capacities. Now suppose one or more additional firms enter with positive capacities. Then aggregate output increases, aggregate output of the m original firms does not increase, and the output of any firm that was originally unconstrained decreases. Finally, the gross profit of each of the m original firms decreases.

Exit Corollary. Suppose again that m firms initially have positive capacities and that one or more of them exit. Then aggregate output decreases, aggregate output of the remaining firms does not decrease, the output of any firm that was initially unconstrained increases, and the output of any firm that was initially constrained remains constant. Finally, the gross profit of each of the remaining firms increases.

Assumption 4 implies a useful proposition concerning net profits of firms in Cournot equilibrium.

Proposition 4. If firms i and j are constrained or semiconstrained, then $[H_i(\cdot) - F(k_i)] - [H_j(\cdot) - F(k_j)]$ has the sign of $(k_i - k_j)$. In words, net profits in a Cournot equilibrium are ranked in order of capacities, provided that the firms being ranked are not unconstrained.

Proof. Since $x_i = k_i$, $H_i(\cdot) - F(k_i) = \left[f(X) - V - \dfrac{F(k_i)}{k_i} \right] k_i$, which, from Assumption 4, is increasing in k_i.

We are interested in the free-entry equilibria of the $(n + 1)$-stage game—the equilibria in which not all of the n firms choose a positive capacity. Hence, we assume that n is so large that if $k_i > 0$ for all i, then some firm (or firms) earns negative profit. For technical reasons, we assume that n is finite.

Assumption 5. The number of firms, n, is finite and is such that if $k_i > 0$ for all i, then $H_j(k_1, \ldots, k_n) - F(k_j) < 0$ for some j.

3. Properties of perfect equilibrium

■ **Preview of results.** Before turning to the analysis of perfect equilibrium, it is useful to preview the main results that we shall establish. We first show that in perfect equilibrium no firm holds excess capacity. This reflects among other things the fact that excess capacity is not a barrier to entry in this model. From the entry corollary we see why. If a firm is unconstrained before entry—if it holds excess capacity—, then not only will it not use the excess capacity after entry, but it will, in fact, hold even more excess capacity. It is clear that the "no-excess-capacity result" depends critically on the demand restriction that marginal revenue of any firm is decreasing in the output of other firms. Bulow, Geanakoplos, and Klemperer (1985) provide an example in which relaxing this restriction can lead to excess capacity in the perfect equilibrium of a simple entry game.

Next we derive a necessary and sufficient statistic for entry. That is, we determine a necessary and sufficient condition for entry of some firm i, given the predetermined capacities of the first $(i - 1)$ firms. The ith firm will enter if and only if its maximized profit, given that firms $(i + 1)$ through n hold zero capacity, is positive. Firm i will not, of course, actually choose capacity in this myopic fashion if it does enter. The condition simply tells us when a firm will enter, and moreover what it means in this model to say that entry is deterred, or that we have a free-entry equilibrium.

The entry proposition also tells us something about the identity of firms in perfect equilibrium and their aggregate output. Suppose there are i firms in perfect equilibrium:

they will be firms 1 through i, the first i firms in the sequence of potential firms. Further, their aggregate output will be no less than the Bain-Labini-Modigliani limit output.

We then come to perhaps the major result characterizing perfect equilibrium. Suppose the first i firms had infinite capacities, which maximizes their leverage with respect to entry of firm $(i + 1)$. It is clearly possible that firm $(i + 1)$ will not be deterred from entering since excess capacity is no barrier to entry. Given Assumption 5, however, there is some *minimum* value of i, less than n, such that if the first i firms held infinite capacities, firm $(i + 1)$ would be deterred from entering. We show that this minimum number of firms that could deter entry is the number of firms that will, in fact, enter in perfect equilibrium.

Finally, we remark that when the number of firms that enter (choose a positive capacity) is "large," for all practical purposes the output is the limit output. Thus, in a sense we are resurrecting the limit-output model. What our analysis adds is a theory of market structure— the number of firms and their market shares are endogenous in our model.

☐ **Nonexistence of equilibrium.** Before we can prove these results we must confront a nonexistence problem. To see the problem, illustrated in Figure 2, we focus on a case in which there are just two potential firms: firm one chooses k_1, firm two chooses k_2, and the firms then play a capacity-constrained quantity game. Firm two's reaction correspondence in Figure 2 comprises two segments—BA and $A'G'$. Given $k_1 = \bar{k}_1$, firm two is indifferent between $\tilde{k}_2$ and $\bar{k}_2$. The line BAG is the ordinary (full-cost) Cournot reaction function— the locus of profit-maximizing values of $x_2 = k_2$, given $x_1 = k_1$. The reaction correspondence is coincident with this reaction function to the left of A. For $k_1 > \bar{k}_1$, firm two's best capacity response is $\bar{k}_2$, which is discretely larger than $\tilde{k}_2$. The discontinuity in firm two's reaction correspondence is defined by the condition that its isoprofit locus through point A be tangent to firm one's variable-cost Cournot reaction function—at point T in the figure. This reaction function is, of course, the boundary between regions II and IV in Figure 1. Hence, in the quantity equilibrium corresponding to any point on $A'G'$, firm one holds excess capacity, but firm two does not. That is, for all (k_1, k_2) on $A'G'$, $x_1 = \bar{k}_1 < k_1$ and $x_2 = \bar{k}_2$. It then follows that firm one's net profit in any Cournot equilibrium corresponding to a point on $A'G'$ is less than its net profit in the Cournot equilibrium corresponding to point A. Hence, firm one will not present firm two with a capacity larger than $\bar{k}_1$.

FIGURE 2

FIRM 2's REACTION CORRESPONDENCE
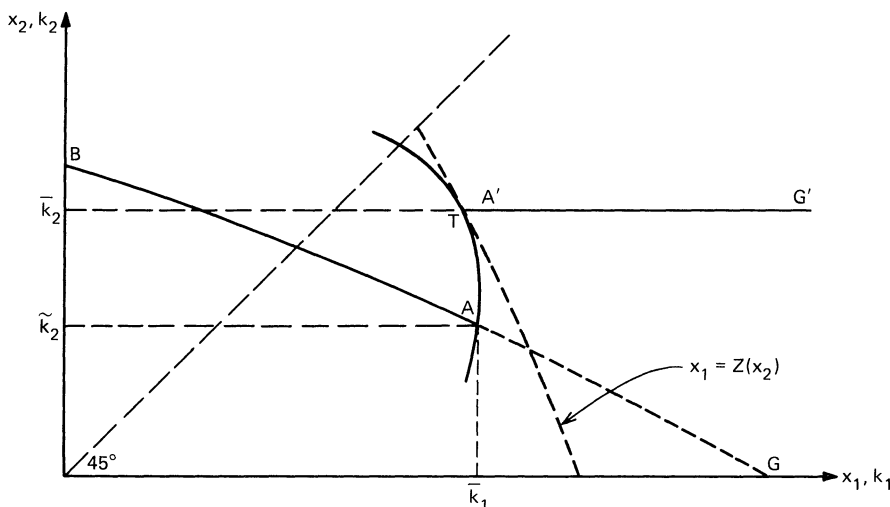
To see the nonexistence problem, suppose that as we move from left to right along BAG, firm one's profit is still increasing at point A. If, given $k_1 = \bar{k}_1$, there is any positive probability that firm two would choose $\bar{k}_2$ instead of $\tilde{k}_2$, then firm one will choose $k_1 < \bar{k}_1$. But then there is no equilibrium, since firm one's profit is increasing on the half-open interval, $[0, \bar{k}_1)$. This problem potentially occurs in any case where n exceeds 1. To avoid it we assume the following.

Assumption 6. If in any subgame any firm is indifferent between two or more capacities, the firm chooses the smallest capacity.

Note that Assumption 6 ensures that all reaction correspondences are reaction *functions*.

□ **No excess capacity.** In examining the case of no excess capacity we offer the following proposition.

Proposition 5. In perfect equilibrium the output of each firm is equal to its capacity.

The argument proceeds as follows. Consider the subgame (defined by) $(k_1, \ldots, k_i)$, and suppose that $x_i < k_i$ in the ensuing subgame-perfect equilibrium. We show that for k_i set equal to the quantity x_i, aggregate output in the corresponding subgame-perfect equilibrium is no larger (and price no smaller) than it was in the equilibrium of the original subgame, and hence that i's output is identical in both. Therefore, firm i's profit increases if it eliminates excess capacity, and excess capacity is inconsistent with perfect equilibrium.

Proof. Consider the subgame $(k^{i-1}, \bar{k}_i)$, where k^{i-1} denotes the vector of capacities $(k_1, \ldots, k_{i-1})$, and denote the subgame-perfect responses of firms $(i + 1)$ through n by $(\bar{k}_{i+1}, \ldots, \bar{k}_n)$ and the aggregate output in the corresponding equilibrium by $\bar{X}$. Suppose that firm i's output in the equilibrium, $\bar{x}_i$, is less than its capacity, $\bar{k}_i$. Now consider the subgame $(k^{i-1}, \tilde{k}_i = \bar{x}_i)$—the subgame in which firm i's capacity, $\tilde{k}_i$, is equal to $\bar{x}_i$—and denote subgame-perfect responses and aggregate output in the corresponding equilibrium by $(\tilde{k}_{i+1}, \ldots, \tilde{k}_n)$ and $\tilde{X}$. We must show that $\tilde{X} \leq \bar{X}$.

Define

$$S = \{k^{i-1}, k_i, \ldots, k_n | X \geq \bar{X}\},$$

and

$$\bar{S} = \{k^{i-1}, k_i, \ldots, k_n | X < \bar{X}\}.$$

If $(k^{i-1}, \tilde{k}_i, \ldots, \tilde{k}_n) \in \bar{S}$, then $\tilde{X} < \bar{X}$, and we are done.

Suppose then that $(k^{i-1}, \tilde{k}_i, \ldots, \tilde{k}_n) \in S$. Observe that for any $(k^{i-1}, \bar{k}_i, k_{i+1}, \ldots, k_n) \in S$ and any $(k^{i-1}, \tilde{k}_i, k_{i+1}, \ldots, k_n) \in S$, $H_j(k^{i-1}, \bar{k}_i, k_{i+1}, \ldots, k_n) = H_j(k^{i-1}, \tilde{k}_i, k_{i+1}, \ldots, k_n)$ for all $j > i$, since i is either unconstrained or semiconstrained (see Proposition 3(d)). This implies that firm n's reaction functions are identical in the two subgames, which in turn implies that firm $(n - 1)$'s reaction functions are also identical, and so on. Hence, $(\tilde{k}_{i+1}, \ldots, \tilde{k}_n) = (\bar{k}_{i+1}, \ldots, \bar{k}_n)$, and therefore $\tilde{X} = \bar{X}$.   *Q.E.D.*

□ **The entry statistic.** Next we find the condition that determines whether a firm will enter, given the capacity choices of all previous firms.

Definition 3. Let $G_i(k^{i-1}) = \max_{k_i > 0} [H_i(k^{i-1}, k_i, 0, \ldots, 0) - F(k_i)]$.

$G_i(k^{i-1})$ is the maximum profit firm i could earn by entering (by choosing $k_i > 0$), given predetermined capacities, k^{i-1}, and given that the capacities of all subsequent firms are zero. That is, $G_i(\cdot)$ is a "myopic" entry signal for firm i, because it is conditioned on no subsequent entry. Proposition 3 implies that $G_i(\cdot)$ is continuous and nonincreasing in

k_j, $j < i$, and strictly decreasing in k_j if k_j is sufficiently small. We show in the following proposition that despite the fact that firm i actually makes its entry decision with perfect foresight about subsequent entry, this myopic calculation yields a statistic that is both necessary and sufficient for entry.

Proposition 6. It is necessary and sufficient for the entry of firm i that $G_i(k^{i-1}) > 0$.

Proof. Necessity is trivial to establish since firm i's profit is nonincreasing in k_j, $j > i$. (We assume for convenience, that a firm anticipating exactly zero profit will not enter.)

To prove sufficiency, let $k_i = \infty$, and consider two cases. If $G_{i+1}(k^{i-1}, k_i = \infty) \leq 0$, then firm i can deter entry. Denote by $\underline{k}_i$ the smallest value of k_i that deters entry, and denote $\underset{\underline{k}_{i+1}>0}{\text{argmax}}\, H_{i+1}(k^{i-1}, \underline{k}_i, k_{i+1}, 0, \ldots, 0) - F(k_{i+1})$ by $\underline{k}_{i+1}$. Then, by continuity we have

$$G_{i+1}(k^{i-1}, \underline{k}_i) = H_{i+1}(k^{i-1}, \underline{k}_i, \underline{k}_{i+1}, 0, \ldots, 0) - F(\underline{k}_{i+1}) = 0.$$

Let $\tilde{k}_i = \max(\underline{k}_i, \underline{k}_{i+1})$, and let $\hat{k}_{i+1} = \min(\underline{k}_i, \underline{k}_{i+1})$. Then, from Proposition 4 we have

$$H_i(k^{i-1}, \tilde{k}_i, \hat{k}_{i+1}, 0, \ldots, 0) - F(\tilde{k}_i) \geq G_{i+1}(k^{i-1}, \underline{k}_i) = 0.$$

But $\tilde{k}_i$ deters entry, and firm i's net profit in the subgame $(k^{i-1}, \tilde{k}_i)$ is

$$H_i(k^{i-1}, \tilde{k}_i, 0, \ldots, 0) - F(\tilde{k}_i),$$

which from the preceding inequality and Proposition 3(c) is positive. Thus, $\tilde{k}_i$ is a profitable entry-deterring strategy for firm i.

If $G_{i+1}(k^{i-1}, k_i = \infty) > 0$, we have the second case. In the subgame defined by $(k^{i-1}, k_i = \infty)$, at least one of the perfect responses, denoted by $(\dot{k}_{i+1}, \ldots, \dot{k}_n)$, will be positive. For example, if $\dot{k}_j = 0$ for all $i < j < n$, then $\dot{k}_n > 0$, since n is the last firm. Let $\dot{x}_i$ denote firm i's output and $\dot{X}$ aggregate output in this subgame-perfect equilibrium, and let j denote a firm, $j > i$, such that $\dot{k}_j > 0$. Observe that

$$H_i(k^{i-1}, k_i = \infty, \dot{k}_{i+1}, \ldots, \dot{k}_n) - F(\dot{x}_i) \geq H_j(k^{i-1}, k_i = \infty, \dot{k}_{i+1}, \ldots, \dot{k}_n) - F(\dot{k}_j) > 0.$$

The first inequality follows from the fact that no firm has an output larger than $\dot{x}_i$ and from Proposition 4. Now consider the subgame $(k^{i-1}, k_i = \dot{x}_i)$, and denote the corresponding subgame-perfect responses by $(\hat{k}_{i+1}, \ldots, \hat{k}_n)$ and aggregate output by $\hat{X}$. The "eliminate excess capacity argument" used to prove Proposition 5 implies that $\hat{X} \leq \dot{X}$ and hence that

$$H_i(k^{i-1}, k_i = \dot{x}_i, \hat{k}_{i+1}, \ldots, \hat{k}_n) \geq H_i(k^{i-1}, k_i = \infty, \dot{k}_{i+1}, \ldots, \dot{k}_n).$$

The last three inequalities imply that $k_i = \dot{x}_i$ is a profitable entry strategy for firm i. *Q.E.D.*

Two corollaries deserve attention.

Corollary 1. If there are i positive capacities in the perfect equilibrium of the $(n + 1)$-stage game, then $k_j > 0$ for $j \leq i$, and $k_j = 0$ for $j > i$.

Corollary 2. Let $\underline{X}$ be the value of aggregate output such that

$$\max_x \{xf(\underline{X} + x) - Vx - F(x)\} = 0.$$

Then, letting X^* denote aggregate output in perfect equilibrium, we see that $X^* \geq \underline{X}$.

That is, in perfect equilibrium output is no smaller than the Bain-Labini-Modigliani limit output. The proof of Corollary 2 is quite simple. From Proposition 5 we know that in perfect equilibrium $\sum_{i=1}^{n} k_i = X^*$, and from Corollary 1 we know that $k_n = 0$. Suppose that $X^* < \underline{X}$; then $G_n(k^{n-1}) > 0$, and hence firm n would enter, which is a contradiction.

□ **Determining the equilibrium number of firms.** Now that we have necessary and sufficient conditions for the entry of firm i, we want to determine the number of firms that will enter in perfect equilibrium. Suppose for the moment that i firms had entered and that each of them had an infinite capacity. Denote this vector of capacities by k_∞^i. It is clear that this maximizes their leverage with respect to the entry of $(i + 1)$, and further that k_∞^i will not necessarily deter entry. Let u be the smallest value of i such that $G_{i+1}(k_\infty^i) \le 0$. The integer u is then the smallest number of firms that could deter entry. We show that in the perfect equilibrium of the $(n + 1)$-stage game, the first u firms will enter and that no other firm will.

Proposition 7. In perfect equilibrium the number of firms entering (choosing positive capacity levels) is the smallest number that can deter the entry of an additional firm.

We present the proof in the Appendix. The structure of the argument is as follows. We consider all subgames (defined by k^i) in which $G_{i+1}(k^i) > 0$: all subgames in which firm $(i + 1)$ enters. We partition these subgames into sets, indexed by $z \ge 1$ and defined as follows:

$$z = \max_{j \in I^+} j \mid G_{i+j}(k^i, k_{i+1} = \infty, k_{i+2} = \infty, \dots, k_{i+j} = \infty) > 0,$$

where I^+ is the set of positive integers. If $z = 1$, entry will be deterred when k_{i+1} is sufficiently large. If $z = 2$, entry will be deterred when k_{i+1} and k_{i+2} are sufficiently large, and so on. We show that the number of firms entering in the perfect equilibrium of any such subgame is z, the index of the subgame. This proves Proposition 7, since the index of the subgame in which no firm has entered is the integer u—the smallest number of firms that can deter the entry of an additional firm.

Consider first the case $z = 1$, and let $\underline{k}_{i+1}$ be the smallest value of k_{i+1} that deters the entry of firm $(i + 2)$. We show that any "accommodation" strategy $k_{i+1} < \underline{k}_{i+1}$ implies a subgame equilibrium that makes firm $(i + 1)$ worse off. We then consider the case $z = 2$, and let $\underline{k}_{i+1}$ denote the smallest value of k_{i+1} such that firm $(i + 2)$ can deter entry. We know from the $z = 1$ case that firm $(i + 2)$ *will* deter entry if $k_{i+1} \ge \underline{k}_{i+1}$. We show that for $z = 2$, any $k_{i+1} < \underline{k}_{i+1}$ will again make firm $(i + 1)$ worse off than it is with $k_{i+1} = \underline{k}_{i+1}$, and hence exactly two firms will enter any subgame in which $z = 2$. The case $z = 3$ is then proved by using the results for $z = 1, 2$, and so on, recursively.

4. Explicit solutions to the model: the case of linear demand

■ Proposition 7 implies a corollary that greatly simplifies the task of finding solutions to explicit parameterizations of the model. The proposition states that the equilibrium number of firms will be the smallest number that can deter entry. But this number is independent of the capacities of firms that do enter. Thus, the process of finding a solution to the model can be decomposed into two stages, first finding the equilibrium number of firms u, and then solving, conditional on u and on the fact that firm $(u + 1)$ is deterred from entering, for the equilibrium vector of capacities, quantities, and the equilibrium price.

In this section we suppose that the inverse demand function is linear:

$$p = 2 - X.$$

Let $F(k_i) = F + \alpha k_i$ and $V = (1 - \alpha)$, so that

$$C(\tilde{x}_i, k_i) = F + \alpha k_i + (1 - \alpha)\tilde{x}_i, \qquad \tilde{x}_i \le k_i,$$

where $0 \le \alpha \le 1$. The parameter α represents the proportion of production costs that are sunk, with unit production costs held constant at unity. A change in α has no effect on total costs, but does affect the degree of strategic advantage that is conferred by the ability to sink capacity in advance of production. The parameter F represents a fixed (and sunk) cost of entry.

□ **The equilibrium number of firms.** We obtain the equilibrium number of firms by deriving in explicit form the boundaries of the (index) partition of the subgame described in the previous section. These boundaries are equivalent to the equations $G_2(k_\infty^1) = 0$, $G_3(k_\infty^2) = 0$, $G_4(k_\infty^3) = 0 \ldots$, where k_∞^i is the vector of infinite capacities for the first i firms. The subgame partition is derived in the parameter space (F, α), and is illustrated in Figure 3. Note that Figure 3 identifies equilibrium "n-opolies," without having solved for the full perfect equilibrium to the model. It is instructive to hold F constant in Figure 3 and to observe what happens to the number of firms as we vary α. An increase in α increases the relative importance of the sunk component of unit production costs. This increases the strategic advantage of earlier entrants, and at discrete values of α will reduce the number of firms in perfect equilibrium. When $\alpha = 1$, all production costs are sunk, and the equilibrium consists of a single firm, for all values of F. That is, the first entrant is able credibly to install sufficient capacity to deter any further entry.

Solutions to the model can be further subdivided into one of two kinds—*blockaded* solutions and *strategic* solutions. To see the nature of the distinction, consider the following exercise. Given u, the number of firms that enter in perfect equilibrium, consider a sequential game of perfect information in which there are exactly u firms. If the solution to this game is identical to the perfect equilibrium solution, we say that the perfect equilibrium solution is *blockaded*. If they are different, which implies that the perfect equilibrium is materially influenced by the potential for entry, we say that the perfect equilibrium solution is *strategic*.

The intuition behind the blockaded solution is elementary and traditional; it is a direct extension of Bain's concept of blockaded monopoly. In a blockaded n-opoly, the incumbent firms can ignore the possibility of entry, although there is strategic interaction among them. The division of all solutions into either blockaded or strategic solutions implies a further subpartition of the technology parameter space, which we illustrate in Figure 4.

Obviously, the threat of *additional* entry has no effect in the parameter regions corre-

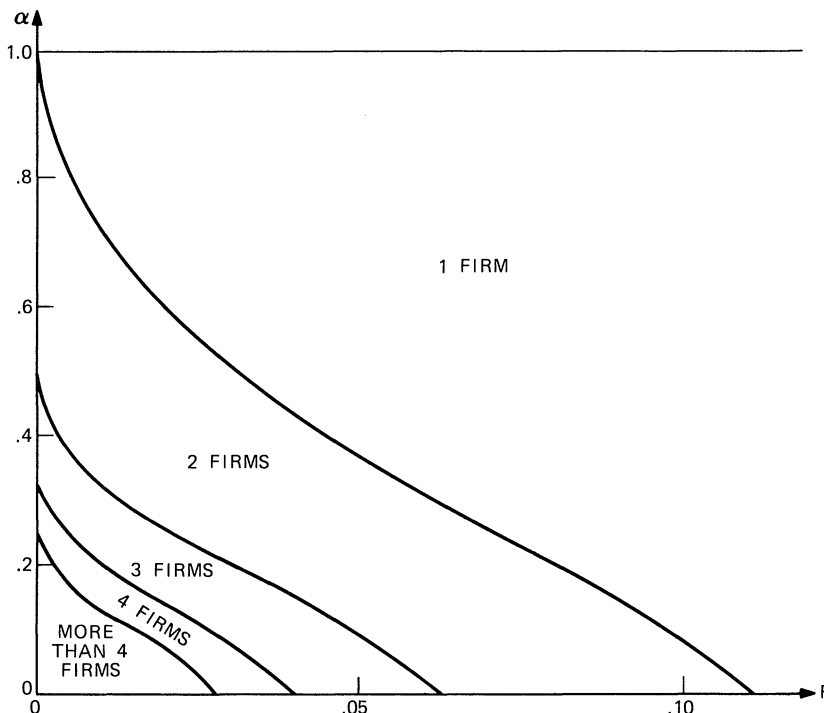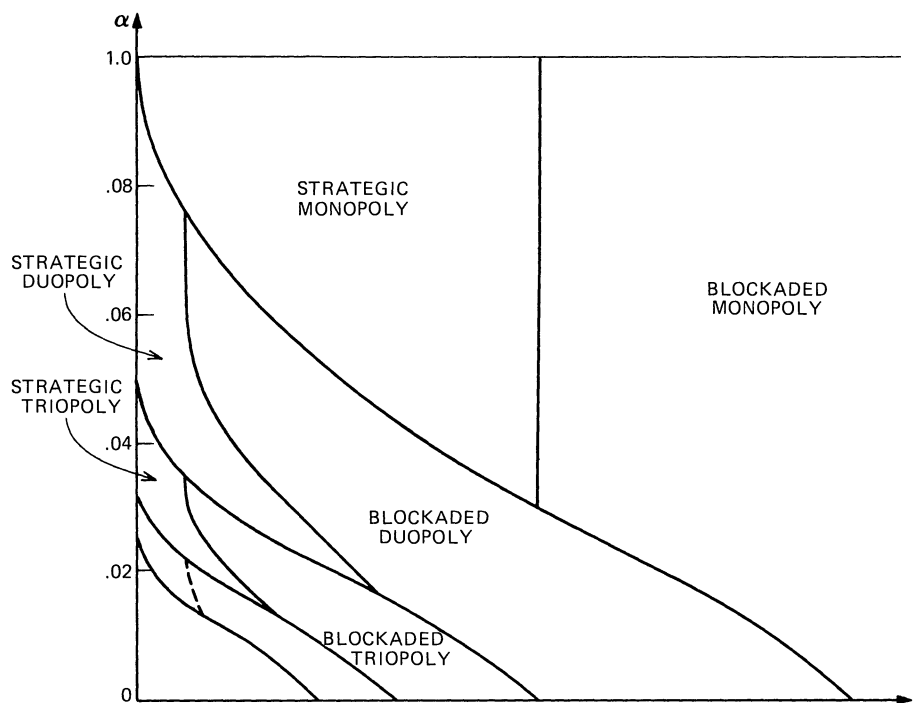FIGURE 3

EQUILIBRIUM NUMBER OF FIRMS

FIGURE 4

BLOCKADED AND STRATEGIC "n—OPOLIES"

sponding to blockaded solutions. These regions cover a large part of the parameter space, and we conjecture that as the number of producing firms increases, the "likelihood" of blockaded solutions becomes progressively larger. This observation suggests at least a different perspective on the idea that potential entry disciplines the market. In our model the strategic interaction between *actual* entrants often has more impact on the final equilibrium than does the need to deter *potential* entrants.

A complete solution to the model requires that each firm's choice of capacity be profit maximizing, given the vector of capacity choices of earlier entrants, and given the subgame equilibrium conditioned by that firm's capacity choice. The monopoly case is simple. In the blockaded case the monopolist's choice is unconstrained. In the strategic case the monopolist installs just enough capacity to deter entry.

We may also obtain analytic solutions to the duopoly case, albeit with some tedious computation.[3] To derive equilibria involving larger numbers of producing firms, we have written a computer algorithm that computes the (approximate) perfect equilibrium to the entry game for parameter values leading to two or three producing firms.[4] Figure 5 reports approximate perfect equilibria to the entry game for technology parameters leading to one, two, or three producing firms.

□   **Size distributions and the threat of entry.** From the results reported in Figure 5, we can analyze the effect on the equilibrium of varying the technology parameters α and F. We begin with the blockaded equilibria. Starting from any blockaded equilibrium, a decrease

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[3] The blockaded duopoly solutions are derived in full in Ware (1984).

[4] The computer algorithm mimics the recursive structure of the sequential game by first finding firm u's best response function, then $(u - 1)$'s, and so on. Details are available from the authors on request.

FIGURE 5

PERFECT EQUILIBRIUM IN F − α SPACE
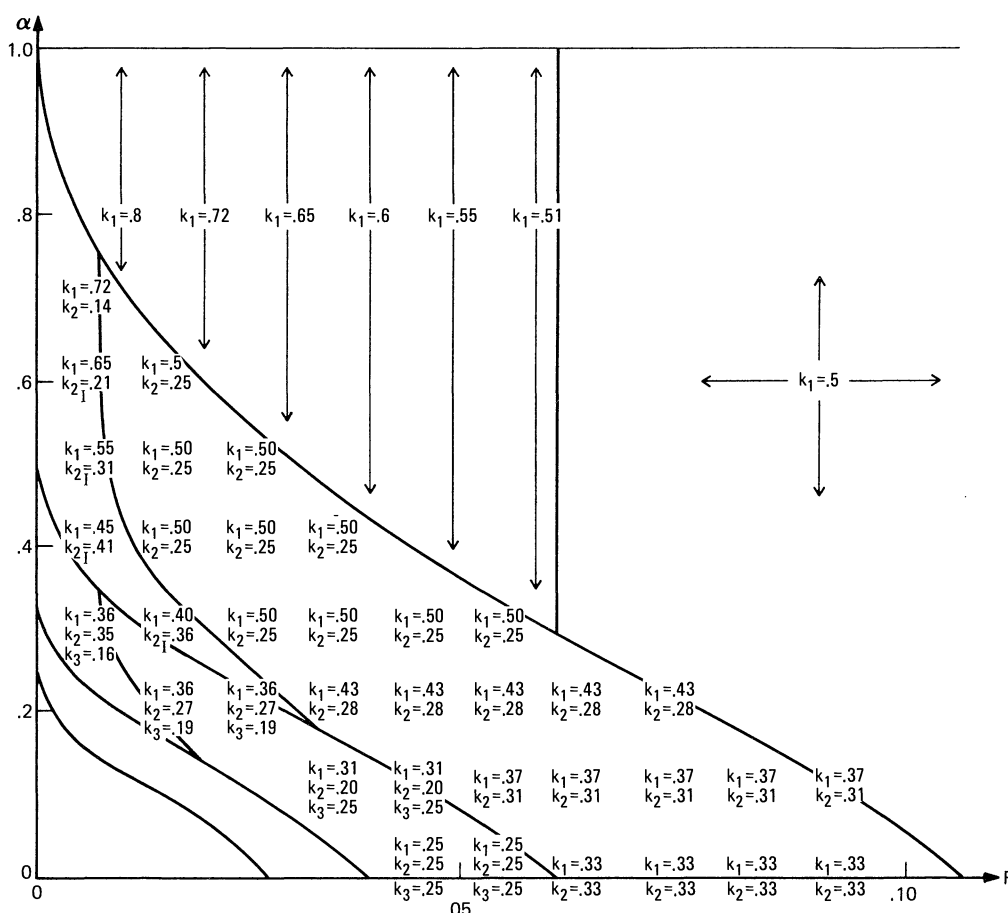
in F, the sunk cost of entry, has no effect on the equilibrium (providing that F does not change sufficiently to permit entry or to produce a strategic equilibrium). The parameter α, the proportion of production costs that are sunk, is a measure of the degree of strategic advantage held by early movers in the sequential game. The effect on the blockaded equilibrium of varying α is as expected: for a given number of firms, a decrease in α leads to a reduced variance of equilibrium firm sizes. Firms that move early are unable to capture so large a share of the market when the strategic advantage of moving early, in the form of sunk production costs, is reduced.

A general result is that the threat of entry reduces the variance of firm sizes. This can be seen in Figure 5, either moving from right to left across a blockaded-strategic boundary, or from right to left within a strategic region. The issue here is the credibility of the incumbents' capacity in deterring entry. Given aggregate industry capacity, greater symmetry of capacities lowers the minimum fixed cost of entry for which deterrence is feasible. Thus, lowering the fixed costs of entry within any strategic region leads to reduced variance of firm sizes in market equilibrium.

☐ **Nonmonotonic market shares.** The results in Spence (1977), Dixit (1980), and Ware (1984) establish that the privilege of being a *first mover* is a valuable one in this type of sequential entry game. An obvious conjecture, consistent with the results in McLean and
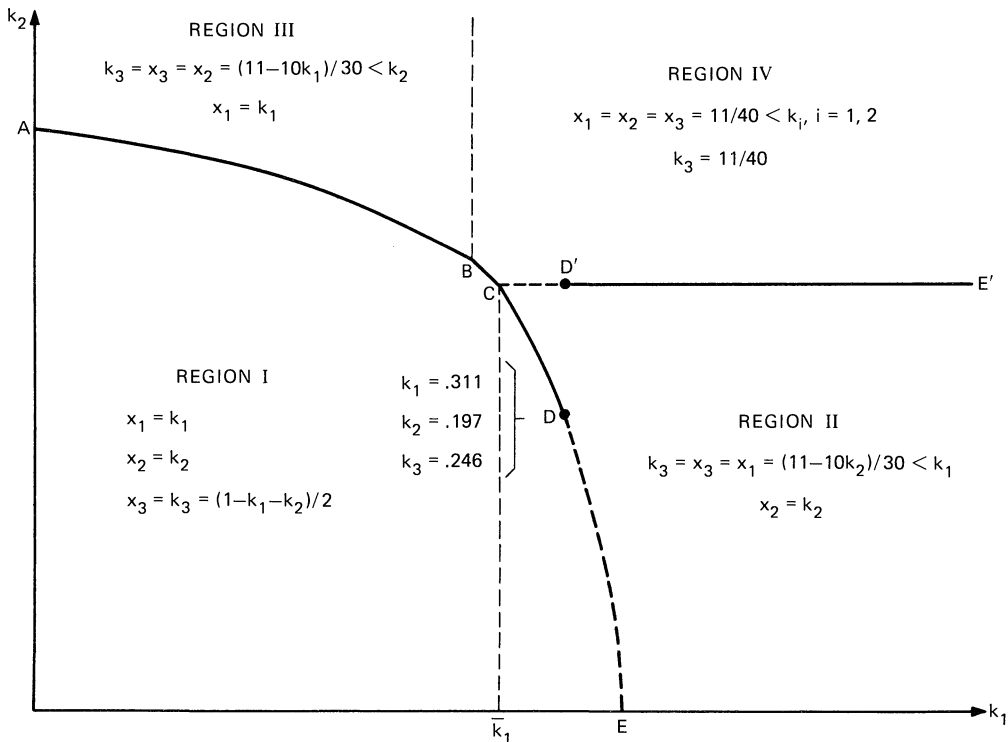
Riordan (1985), is that the privilege of being an *early mover* is likewise valuable. Surprisingly, in our model the profit of a firm early in the sequence of entrants is not necessarily larger than (or equal to) the profit of firms later in the sequence. For example, as Figure 5 reveals, when $F = .045$ and $\alpha = .1$, firm three is larger and more profitable than firm two.

To understand this curious result, focus first on firm three's capacity decision, given (k_1, k_2). In this particular case ($F = .045$ and $\alpha = .1$) the existence of a fourth potential firm has no bearing on the equilibrium, since it is a three-firm blockaded equilibrium. This allows us to compute in a straightforward, if tedious, manner the perfect equilibrium for all subgames (k_1, k_2). We record the results in Figure 6.[5] In region I all three firms are constrained, in region IV both firm one and firm two are unconstrained, and in region II (III) firm one (firm two) is unconstrained and firm two (firm one) is constrained.

Now focus on firm two's reaction function. In region I firm two's profit is increasing in k_2 for all k_1. As k_2 passes through the line $ABCDE$, firm two's profit drops discretely, since subgames (k_1, k_2) in regions II, III, and IV induce firm three to choose a capacity discretely larger than the capacity it chooses on $ABCDE$. In regions III and IV, firm two is unconstrained (it holds excess capacity), and hence its reaction function for $k_1 \leq \bar{k}_1$ is ABC. For subgames in which $k_1 > \bar{k}_1$, firm two must choose between an equilibrium on CDE in region I and the best equilibrium in region II. In region II its best response is on the line $CD'E'$. For $k_1 \leq .311$, its profit on CDE is larger, and for $k_1 > .311$, its profit on $CD'E'$ is larger. Hence, its reaction function comprises two segments—$ABCD$ and $D'E'$.

Finally, consider firm one's choice. It will choose the point on firm two's reaction

FIGURE 6

REACTION FUNCTION OF FIRM 2 IMPLICIT IN A NONMONOTONIC PERFECT EQUILIBRIUM (AT POINT D)

REGION III

$k_3 = x_3 = x_2 = (11-10k_1)/30 < k_2$

$x_1 = k_1$

REGION IV

$x_1 = x_2 = x_3 = 11/40 < k_i,\ i = 1, 2$

$k_3 = 11/40$

REGION I

$x_1 = k_1$

$x_2 = k_2$

$x_3 = k_3 = (1-k_1-k_2)/2$

$k_1 = .311$

$k_2 = .197$

$k_3 = .246$

REGION II

$k_3 = x_3 = x_1 = (11-10k_2)/30 < k_1$

$x_2 = k_2$

---

[5] In Figure 6 the locus AB is defined by $(1 - k_1 - k_2)^2/4 = (11 - 10k_1)(8 - 10k_1)/900$, the locus BC by $(1 - k_1 - k_2)^2/4 = 77/1600$, and the locus CE by $(1 - k_1 - k_2)^2/4 = (11 - 10k_2)(8 - 10k_2)/900$.

function that offers it the largest profit. Moving from left to right along $ABCDE$, firm one's profit is still increasing at D, and its profit at D is larger than its profit at any point on $D'E'$, since it holds excess capacity in region II. Hence, firm one chooses $k_1 = .311$ and induces firms two and three to choose $k_2 = .197$ and $k_3 = .246$.

The key to the intuitive understanding of this result is the observation that the equilibrium profit of firm two (and of firm one) in any subgame (k_1, k_2) is discontinuous along $ABCDE$. Below the line, small changes in k_1 or k_2 induce small changes in k_3. Beginning at any point on the line, a small increase in k_1 or k_2 induces firm three to increase its capacity discretely, which action discretely reduces the profit of firm two. That is, on the line $ABCDE$ small increases in k_1 or k_2 induce a large increase in k_3 and a discrete decrease in firm two's profit. It is this discontinuity that allows firm one to force the solution at D. In moving to the right along $ABCD$, firm one is squeezing firm two and knows that firm two will reduce k_2 to avoid the discrete drop in its profit that any subgame above $ABCDE$ promises. At point D firm two has been pushed to the limit, and any further increase in k_1 would induce firm two to increase its capacity discretely, and thus to reduce firm one's profit.

The result that profits are not invariably decreasing in the order in which firms enter calls into question the applicability of our model. At a minimum, it suggests that one should incorporate the possibility that firms will attempt to manipulate the order of entry by refusing to enter when their turn comes. Any model that allows for this sort of "wait and see" strategy will, of course, be more complex.

5. Conclusions

■ Recent contributions in theoretical industrial organization, notably those of Spence (1977) and Dixit (1980), have pointed the way toward the development of a theory of market structure. Although these models do not offer a complete theory of market structure, because the entry game is restricted to a single incumbent facing a single potential entrant, it is clear that a theory of market structure is embedded in their assumptions of strategic behavior and sequential entry.

In this article we have developed a theory of market structure suggested by the work of these earlier authors. Firms enter the market in sequence, each computing the reaction of all subsequent entrants to its own strategic investment decision. Only demand and cost conditions and the structure of the entry game are specified exogenously; the number of firms, their size distribution, and the market price are determined as the equilibrium to this entry game.

In a sense, the theory is an elaboration of the Bain-Labini-Modigliani limit-output or limit-price model. Aggregate output in equilibrium is always approximately equal to the limit output. The fact that output is never less than the limit output also has implications for efficiency. Roughly, firms use their power of strategic commitment to obtain as large a share of the market equilibrium quantity as they can. Thus, each firm acts to minimize the number of subsequent entrants. By reducing the number of firms in equilibrium, and hence economizing on entry costs, such behavior tends to improve welfare.

A reservation concerning the model is the artificial "order of entry," which is essential to determining equilibrium market structure. The most spectacular rivalry in many markets—the scramble to establish priority—is ignored in our analysis. Our model is perhaps least useful in understanding the evolution of market structure in such industries.

Our model seems most applicable to explaining entry into an established industry. Any potential entrant must obviously confront the irreversible decisions made by his predecessors, and it must take into account the possibility of subsequent entry by other firms. Indeed, a question that naturally arises is whether such an industry is in entry equilibrium. To answer this question, we believe that one must adopt the analytical framework (broadly defined) used in this article. Entry by its very nature is sequential, and rational entry requires analysis of a sequential game of the kind we develop.

From this perspective, Proposition 6 is particularly interesting. It says that one can answer the "entry equilibrium" question by putting oneself in the frame of reference of a *myopic* entrant—an entrant who makes his entry decision on the basis that there will be no subsequent entry.

Appendix

■   The proof of Proposition 7 follows.

Proof of Proposition 7. We consider all subgames in which $G_{i+1}(k^i) > 0$. We partition these subgames into sets indexed by $z \geq 1$ and defined as follows:

$$z = \max_{j \in I^+} j \mid G_{i+j}(k^i, k_{i+1} = \infty, k_{i+2} = \infty, \dots, k_{i+j} = \infty) > 0,$$

where I^+ is the set of positive integers. We must show that in the perfect equilibrium of any such subgame, exactly z firms enter.

Case z = 1. Consider the case $z = 1$, and let $\underline{k}_{i+1}$ be the smallest value of k_{i+1} such that $G_{i+2}(k^i, k_{i+1}) \leq 0$. By continuity, $G_{i+2}(k^i, \underline{k}_{i+1}) = 0$. Let $\underline{k}_{i+2}$ be the value of k_{i+2} implied by the maximization that defines $G_{i+2}(\cdot)$. If $\check{k}_{i+1} < \underline{k}_{i+1}$, then there will be $m > i + 1$ firms in the perfect equilibrium of the subgame $(k^i, \check{k}_{i+1})$. Denote this equilibrium by $(k^i, \check{k}_{i+1}, \dots, \check{k}_m, 0, \dots, 0)$. We consider four equilibria of the Cournot game in stage $(n + 1)$ associated with the following capacity vectors: $(k^i, \underline{k}_{i+1}, 0, \dots, 0)$, $(k^i, \underline{k}_{i+1}, \underline{k}_{i+2}, 0, \dots, 0)$, $(k^i, \check{k}_{i+1}, \dots, \check{k}_m, 0, \dots, 0)$, and $(k^i, \check{k}_{i+1}, \dots, \check{k}_m, k_{m+1} = \underline{k}_{i+2}, 0, \dots, 0)$. The first of these has $(i + 1)$ firms with positive capacity, the second $(i + 2)$, the third m, and the fourth $(m + 1)$. Let X_u^v denote the aggregate output of the first u firms in the v-firm Cournot equilibrium and let x_j^v denote the output of firm j in the v-firm Cournot equilibrium.

To show that $(i + 1)$ will deter entry (that is, choose $k_{i+1} \geq \underline{k}_{i+1}$), it is sufficient to show that $X_m^m \geq X_{i+1}^{i+1}$, since price in the $(i + 1)$-firm equilibrium is then no smaller than it is in the m-firm equilibrium, and since $x_{i+1}^m \leq \check{k}_{i+1} < \underline{k}_{i+1} = x_{i+1}^{i+1}$. Assume the opposite:

$$X_m^m < X_{i+1}^{i+1}. \tag{A1}$$

Then

$$X_i^m \geq X_i^{i+1}, \tag{A2}$$

since the marginal revenue of each of the first i firms is greater in the m-firm Cournot equilibrium than it is in the $(i + 1)$-firm equilibrium. Moreover,

$$X_{m+1}^{m+1} \geq X_{i+2}^{i+2}, \tag{A3}$$

and

$$X_m^{m+1} \geq X_{i+1}^{i+2}. \tag{A4}$$

Otherwise, firm $(m + 1)$ would not be deterred, and $(\check{k}_{i+2}, \dots, \check{k}_m, 0, \dots, 0)$ would not be subgame perfect responses to $(k^i, \check{k}_{i+1})$. By the same reasoning that led to (A2), inequality (A3) implies that

$$X_i^{m+1} \leq X_i^{i+2}. \tag{A5}$$

From Proposition 2, inequalities (A4) and (A5), and the fact that $\underline{k}_{i+1}$ is the minimum value of k_{i+1} that deters entry, we have

$$x_{i+1}^m + \dots + x_m^m \geq x_{i+1}^{m+1} + \dots + x_m^{m+1} \geq x_{i+1}^{i+2} = \underline{k}_{i+1} = x_{i+1}^{i+1}. \tag{A6}$$

The first inequality follows from Proposition 2, the second from subtracting (A5) from (A4), and the equalities from the definition of $\underline{k}_{i+1}$. From (A6) we have

$$x_{i+1}^m + \dots + x_m^m \geq x_{i+1}^{i+1}. \tag{A7}$$

Adding (A7) and (A2), we have $X_m^m \geq X_{i+1}^{i+1}$, which contradicts (A1). Hence, in any subgame with index $z = 1$, precisely one firm will enter.

Case z = 2. Now consider the case $z = 2$. Let us, we hope without confusion, redefine $\underline{k}_{i+1}$ as the smallest value of k_{i+1} such that $G_{i+3}(k^i, \underline{k}_{i+1}, k_{i+2} = \infty) \leq 0$. That is, $\underline{k}_{i+1}$ is the smallest value of k_{i+1} such that firm $(i + 2)$ *can* deter the entry of firm $(i + 3)$. If $k_{i+1} \geq \underline{k}_{i+1}$, the index of the implied subgame, (k^i, k_{i+1}), is 1, and from above we know that firm $(i + 2)$ *will* deter entry. We shall show that firm $(i + 1)$ prefers $\underline{k}_{i+1}$ to any $\check{k}_{i+1} < \underline{k}_{i+1}$, and hence that precisely two firms enter in any subgame with index $z = 2$.

Denote the subgame-perfect responses to $(k^i, \underline{k}_{i+1})$ by $(\underline{k}_{i+2}, 0, \dots, 0)$. First, we establish that $G_{i+3}(k^i, \underline{k}_{i+1}, \underline{k}_{i+2}) = 0$. To see this switch $\underline{k}_{i+1}$ and $\underline{k}_{i+2}$ in the investment sequence. This makes no difference to firm $(i + 3)$'s opportunity set. Observe that since $\underline{k}_{i+1}$ is the smallest value of k_{i+1} that allows firm $(i + 2)$ to deter entry, then, given $k_{i+1} = \underline{k}_{i+2}$, $k_{i+2} = \underline{k}_{i+1}$ is the smallest value of k_{i+2} that will deter entry, so that $G_{i+3}(k^i, \underline{k}_{i+1}, \underline{k}_{i+2}) = 0$.

Let $\underline{k}_{i+3}$ be the value of k_{i+3} implied by the maximization that defines $G_{i+3}(\cdot)$. If $\tilde{k}_{i+1} < \underline{k}_{i+1}$, then there will be $m > (i + 2)$ firms in the perfect equilibrium of the subgame $(k^i, \tilde{k}_{i+1})$. Denote this equilibrium by $(k^i, \tilde{k}_{i+1}, \ldots, \tilde{k}_m, 0, \ldots, 0)$. We again consider four equilibria of the Cournot game in stage $(n + 1)$ associated with the following capacity vectors:

$$(k^i, \underline{k}_{i+1}, \underline{k}_{i+2}, 0, \ldots, 0), \qquad (k^i, \underline{k}_{i+1}, \underline{k}_{i+2}, \underline{k}_{i+3}, 0, \ldots, 0),$$

$$(k^i, \tilde{k}_{i+1}, \ldots, \tilde{k}_m, 0, \ldots, 0), \qquad \text{and} \qquad (k^i, \tilde{k}_{i+1}, \ldots, \tilde{k}_m, k_{m+1} = \underline{k}_{i+3}, 0, \ldots, 0).$$

To show that firm $(i + 1)$ prefers $\underline{k}_{i+1}$ to $\tilde{k}_{i+1} < \underline{k}_{i+1}$ it is sufficient to show that $X_m^m \geq X_{i+2}^{i+2}$, where X_u^v again denotes the aggregate output of the first u firms in the v-firm Cournot equilibrium. Suppose the contrary,

$$X_m^m < X_{i+2}^{i+2}. \tag{A8}$$

By the reasoning used to establish (A2), we have

$$X_i^m \geq X_i^{i+2}. \tag{A9}$$

By the reasoning used to establish (A6), we have

$$x_{i+1}^m + \ldots + x_m^m \geq x_{i+1}^{m+1} + \ldots + x_m^{m+1} \geq \underline{k}_{i+1} + \underline{k}_{i+2} = x_{i+1}^{i+2} + x_{i+2}^{i+2}. \tag{A10}$$

Adding (A9) and (A10), we have $X_m^m \geq X_{i+2}^{i+2}$, which contradicts (A8). Hence, in any subgame with index $z = 2$, precisely two firms will enter.

Replication of this argument establishes that in any subgame, with index z, exactly z firms enter in perfect equilibrium. The index of the subgame in which there is no committed capacity is, of course, the smallest number of firms that can deter entry of an additional firm. Q.E.D.

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