Signal Jamming and Limit Pricing: A Unified Approach, in *Public Policy and Economic Analysis*, eds., Moriki Hosoe and Eric Rasmusen, Fukuoka, Japan: Kyushu University Press, 1997.

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Abstract

In signal jamming, an rival uses observed profits to predict profitability, but those profits can be manipulated by a rival firm. In the present model, the size of the market is known to the incumbent, who is one of two firms that might occupy it. The potential rival observes profits, which can be manipulated by the incumbent. Depending on the monopoly premium and the prior probability that the market is large, the equilibrium may be pooling in pure or mixed strategies, or separating, which are similar to the signal-jamming and signalling equilibria of Fudenberg & Tirole (1986) and Milgrom & Roberts (1982a) respectively. In contrast to the common result that strategic behavior encourages innovation even though it introduces current distortions, in this model the possibility of strategic behavior can either encourage or discourage entry into markets as yet unserved by any firm.

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1. Introduction

EMPIRICAL MOTIVATION HERE Every once in a while I think of an invention and have a fantasy of starting up a business. David Friedman, for example, suggested to me that neckties should be sold in different lengths for different sized people. Let's think about the trouble of trying to implement that suggestion. THe cost would be relatively easy to determine. I would buy my neckties from some manufacturer, made to my designs, and Icould get bids on that. My costs would be common knowledge intheindustry, as, indeed, most firms' costs would be.

Demand is another matter. The reason the market does not exist now is because nobody else thinks it is big enough to be profitable. I think differnetly, and I will find out. Suppose I am right, nad the market is profitable. What is my next big problem?

My big problem is entry by competitors. At best, they could enter and force me to share the profits. More likely, they have lower costs than me, and better marketing, and they will wipe me out. So my number one problem is to prevent entry. I can't do this credibly by pretneding to be irratoinal, or bankrupting my competitors, etc. But I might be able to do so by persuading them that the market is not big enough for two firms to operate in.

So,I must not appear too profitable. I may purposely keep my sales and profits small to make the markt appaer unprofitable, even though my continued existence in the market will convey SOME information.

Note that my competitors can observe a lot of things and still not know whether the market is large or not. They can certainly see my prices.They migt be albe to see my output and my profits. BUt even seeing all of these does not necessarily tell them whether themarket couldhold two firms.

There are two ways this could work out. Maybe my competitors can roughly see how well I am doing even if they do not operate themselves.Then my porfit-reducng tactic will be LIMIT PRICING.

Or, maybe my competitors have to enter to get a feel for the market.Then my profit-reducing tactic will bePREDATORY PRICNG,though reallyI may still be pricng above cost.

This is a model of predatory or limit pricing, depending on whether the rival needs to enter or not to discover themarket conditions.

I will model this situation. Many models of predation and limit pricing exist. In brief, the model below differs by being based on demand uncertainty and by involving signalling and signal jamming in the same model. A survey of the literature appears below in Section 3.

Section 2 will lay out the limit pricing model and find the equilibrium. Section 3 will interpret the results and discuss the literature on predation and limit pricing. Section 4 will take the limit pricing model a step back to the source of the incumbent's informational advantage and his original entry decision, to help answer the question of whether strategic entry deterrence encourages innovation or not. Section 5 concludes.

2. Model I: Limit Pricing

There are two firms, an incumbent and an rival. Each firm incurs fixed cost C per period that it is active in the market and earns a net operating revenue of R per period if both firms are in the market. If the incumbent is alone, its revenue is RM, with $M > 1$.[1] The market is *Small* with probability θ and *Large* with probability $1-\theta$. In each period the incumbent chooses R to be either R_0 or R_1 if the market is small and R_1 or R_2 if it is large, where $R_0 < R_1 < R_2$. Assume that $R_2 - C > 0$, $R_1 - C < 0$, and $R_1 M - C > 0$, so a large market can support two firms profitably but a small market can only support one. The payoffs for each firm is the sum of the profits from operations in the two periods. Both firms are risk neutral and do not discount future profits.

The incumbent is already operating in the market in period 1 and by assumption will remain with probability one.[2] The rival cannot observe the size of the market directly and must try to deduce it from R. Having made his estimate, he decides whether to be in or out of the market in the second period.

The variable R is a convenient way to model an imperfect indicator of market size that is correlated with the incumbent's profits. The aim is to analyze as simply as possible a market in which the rival cannot rely on public information to determine the market's size. It could be that the rival observes both price and quantity, but still cannot determine the market size; to observe one price-quantity combination is to observe just one point on the demand curve, and what the rival cares about is the point on the demand curve that would be reached in nonstrategic duopoly competition.

[1] If the product is homogeneous, $M > 2$ is appropriate, but the model allows for heterogeneous products, in which case the industry's duopoly revenue might be greater than the monopoly revenue.

[2] xxx fix this: Otherwise, the two firms are in a "Chicken" game, each vying to be the sole survivor if the market is small. The expected payoffs for each firm in the second-period Chicken subgame would equal zero in the symmetric mixed-strategy equilibrium. A limit pricing model based on this would not behave very differently from Model II below if an entry fee were also included, because the rival would stay out if the market were small to avoid paying the entry fee in exchange for an expected subgame payoff of zero. A model like Model I, however, in which the rival begins in the market but is ignorant of its size, would result in the paradox of the rival unintentionally driving out the incumbent. The incumbent, knowing that the market was small, would exit before incurring the losses of the first period, since the expected subgame payoff would be zero, but the rival, not knowing the market was small, would have no such incentive to exit.

Observing the incumbent's monopoly or strategic duopoly price and quantity does not pin down what the nonstrategic duopoly profit would be, especially if other features besides price influence demand. If the rival observes that the incumbent's price and profits are moderate, this might be either because the market is truly small or because the incumbent is charging less than the monopoly price in a large market. Whether a price is high is a relative matter, and the rival cannot tell whether it is high relative to what the market could bear unless he knows the size of the market to begin with; it is even possible that the monopoly price might be higher in a smaller market. The three revenue levels represent two extremes that reveal the market size, R_0 and R_2, and a moderate revenue that that is uninformative, R_1. The assumption that there exists a revenue level R_0 that definitively reveals a small market is important; what happens if it is relaxed is discussed below. The assumption that the monopoly revenue is M times the duopoly revenue, regardless of whether the market is large or small, may seem arbitrary. Its justification is purely heuristic: this assumption permits a single variable, M to be used to parametrize the value of being a monopoly, rather than requiring two variables, one for each size of market.

The Order of Play in Model I

1. Nature chooses the market to be *Small* with probability θ and *Large* with probability $(1-\theta)$, observed only by the incumbent.

2. The incumbent chooses R to equal R_0 or R_1 for the first period if the market is small, R_1 or R_2 if it is large.

3. The players both observe the incumbent's first-period profits.

4. The rival decides whether to be *In* or *Out* of the market.

5. The incumbent chooses R to equal R_0 or R_1 for the second period if the market is small, R_1 or R_2 if it is large.

6. The incumbent and rival collect their second-period profits, which equal $R-C$ apiece if both are in the market, $RM-C$ and 0 if the incumbent is alone.

The equilibrium takes one of four types, depending on the parameter values. Parameter M, which measures the value of being a monopoly instead of a duopoly, is what matters most to the incumbent's strategy, since it reflects the benefits of entry deterrence. Parameter θ, which measures the prior probability that the market is small, is what matters most to the rival's strategy, since it reflects the probability that an apparently small market truly is small. Figure 1 shows which parameter values are associated with which equilibria.[3] In every equilibrium the incumbent will choose R_2 in the second period if the market is $Large$ and R_1 if it is $Small$, since there is no point in reducing profits once the rival has made his decision, so this decision will be dropped from the equilibrium description. Given this behavior, $In|R_2$ and $Out|R_0$ will be dominant for the rival, since R_2 and R_0 definitely communicate the size of the market.

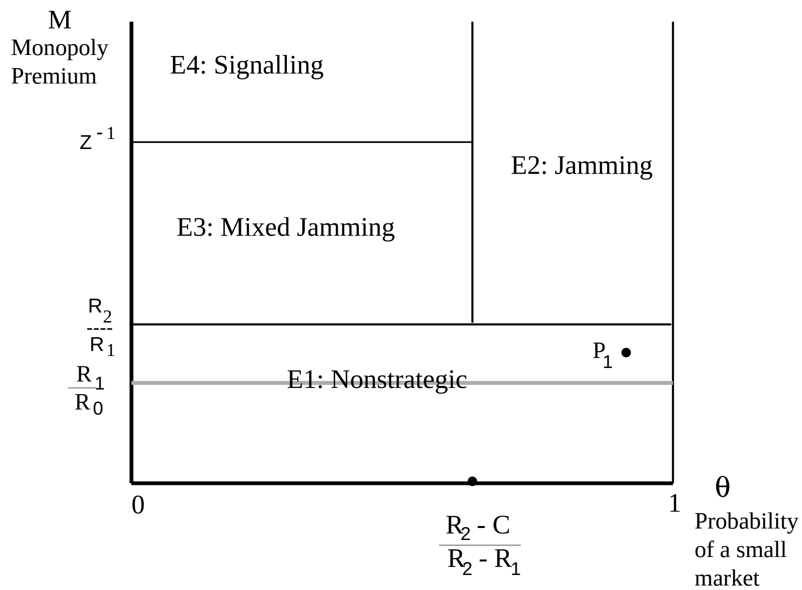

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Figure 1: The Equilibria for Different Parameter Regions

PROPOSITION 1: The four possible equilibria of the limit pricing model are

[3]Please note that in some cases $\frac{R_1}{R_0} > Z^{-1}$, even though the opposite is drawn on the diagram.

(E1) NONSTRATEGIC. $R_2|Large$, $R_1|Small$, $Out|R_0$, $Out|R_1$, $In|R_2$.
(E2) PURE SIGNAL-JAMMING. $R_1|Large$, $R_1|Small$, $Out|R_0$, $Out|R_1$, $In|R_2$.
(E3) MIXED SIGNAL-JAMMING. ($R_1|Small$, $R_1|Large$ with probability α, $R_2|Large$ with probability $(1-\alpha)$, $Out|R_0$, $In|R_1$ with probability β, $Out|R_1$ with probability $(1-\beta)$, $In|R_2$.
(E4) SIGNALLING. $R_0|Small$, $R_2|Large$, $Out|R_0$, $In|R_1$, $In|R_2$.

PROOF: There are four equilibria to consider.

(E1) NONSTRATEGIC. $R_2|Large$, $R_1|Small$, $Out|R_0$, $Out|R_1$, $In|R_2$.

The incumbent's equilibrium payoff in a large market is $\pi_I(R_2|Large) = (MR_2 - C) + (R_2 - C)$, compared with the deviation payoff of $\pi_I(R_1|Large) = (MR_1 - C) + (MR_2 - C)$. The incumbent has no incentive to deviate if $\pi_I(R_2|Large) - \pi_I(R_1|Large) = (1+M)R_2 - M(R_1 + R_2) \geq 0$, which is equivalent to

$$M \leq \frac{R_2}{R_1}. \tag{1}$$

Inequality (1) is a necessary condition for the equilibrium to be nonstrategic. The rival will not deviate from equilibrium, because the incumbent's choice fully reveals the type of market, and under the assumptions that $R_2 - C > 0$ and $R_1 - C < 0$, remaining in the market is only profitable if it is large.

(E2) PURE SIGNAL-JAMMING. $R_1|Large$, $R_1|Small$, $Out|R_0$, $Out|R_1$, $In|R_2$.

The rival's strategy is the same as in E1, so the incumbent's optimal behavior remains the same: for the incumbent to choose R_1, the converse of (1) must be true, and

$$M \geq \frac{R_2}{R_1}. \tag{2}$$

If the rival stays out, his second-period payoff is 0. If he enters, its expected value is $\theta(R_1 - C) + (1-\theta)(R_2 - C)$. Hence, he will follow the equilibrium behavior of staying out if

$$\theta \geq \frac{R_2 - C}{R_2 - R_1}. \tag{3}$$

Conditions (2) and (3) are the necessary conditions for equilibrium E2.

(E3) MIXED SIGNAL-JAMMING. ($R_1|Small$, $R_1|Large$ with probability α, $R_2|Large$ with probability $(1-\alpha)$, $Out|R_0$, $In|R_1$ with probability β, $Out|R_1$ with probability $(1-\beta)$, $In|R_2$.

If $M > \frac{R_2}{R_1}$ but $\theta < \frac{R_2-C}{R_2-R_1}$, neither E1 nor E2 remain as equilibria. If the incumbent played $R_2|Large$ and $R_1|Small$, the rival would interpret R_1 as indicating a small market—an interpretation which would give the incumbent incentive to play $R_1|Large$. But if the incumbent always plays R_1, the rival would enter even after observing R_1, knowing there was a high probability that the market was really large. Hence, the equilibrium must be in mixed strategies, which is equilibrium E3, or the incumbent must convince the rival to stay out by playing R_0, which is equilibrium E4.

For the rival to mix, he must be indifferent between the second-period payoffs of $\pi_E(In|R_1) = \frac{\theta}{\theta+(1-\theta)\alpha}(R_1 - C) + \frac{(1-\theta)\alpha}{\theta+(1-\theta)\alpha}(R_2 - C)$ and $\pi_E(Out|R_1) = 0$. Equating these two payoffs and solving for α gives $\alpha = \left(\frac{\theta}{1-\theta}\right)\left(\frac{C-R_1}{R_2-C}\right)$, which is always non-negative, but avoids exceeding one only if

$$\theta \leq \frac{R_2 - C}{R_2 - R_1}, \tag{4}$$

a necessary condition for equilibrium E3. For the incumbent to mix when the market is large, he must be indifferent between $\pi_I(R_2|Large) = (MR_2 - C) + (R_2 - C)$ and $\pi_I(R_1|Large) = (MR_1 - C) + \beta(R_2 - C) + (1-\beta)(MR_2 - C)$. Equating these two payoffs and solving for β gives $\beta = \frac{MR_1 - R_2}{(M-1)R_2}$, which is strictly less than one, and which is non-negative if $MR_1 - R_2 \geq 0$, condition (2).

If the market is small, the incumbent's alternative payoffs are the equilibrium payoff of $\pi_I(R_1|Small) = (MR_1 - C) + \beta(R_1 - C) + (1-\beta)(MR_1 - C)$ and the deviation payoff of $\pi_I(R_0|Small) = (MR_0 - C) + (MR_1 - C)$. The difference is

$$\pi_I(R_1|Small) - \pi_I(R_0|Small) = [MR_1 + \beta R_1 + (1-\beta)MR_1] - [MR_0 + MR_1] \tag{5}$$

This difference is non-negative under either of two conditions. It is non-negative if R_0 is small enough; that is, if

$$R_0 \leq R_1\left(1 - \frac{R_1}{R_2}\right). \tag{6}$$

Even if inequality (6) is false, the difference is nonnegative if M is no greater than some amount Z^{-1} defined as follows:

$$M \leq \left(\frac{R_1}{R_2} - 1 + \frac{R_0}{R_1}\right)^{-1} = Z^{-1}. \tag{7}$$

Note that if condition (6) is false, then $Z^{-1} > \frac{R_2}{R_1}$, because $Z < \frac{R_1}{R_2}$ and $Z > 0$.[4] Thus, we can draw region E3 as it is shown in Figure 1.

(E4) SIGNALLING. $R_0|Small$, $R_2|Large$, $Out|R_0$, $In|R_1$, $In|R_2$.

It follows from the discussion of E3 that if condition (4) is true but (7) is replaced by its converse, then the unique equilibrium is for the incumbent to choose $R_0|Small$. Out-of-equilibrium beliefs that support this are that if the rival observes R_1, he believes the market is large with probability $\frac{(1-\theta)\alpha}{\theta+(1-\theta)\alpha}$, as in equilibrium E3. Greater values of $Prob(Large|R_1)$ also support the equilibrium, including the passive conjecture of $Prob(Large|R_1) = 1 - \theta$.

The signalling equilibrium is also an equilibrium for other parameter regions. Let the out-of-equilibrium belief be $Prob(Large|R_1) = 1$. The equilibrium payoff is $\pi_I(R_0|Small) = (MR_0 - C) + (MR_1 - C)$ and the deviation payoff is $\pi_I(R_1|Small) = (MR_1 - C) + (R_1 - C)$. The signalling equilibrium remains an equilibrium so long as

$$M \geq \frac{R_1}{R_0}. \tag{8}$$

There exist multiple equilibria for those parts of E1, E2, and E3 that overlap with the area defined by (xxx). □

In E1, limit pricing would not work and is not even attempted. In E2, it is always used successfully: the incumbent sacrifices profits in period one to avoid revealing the market's size. In E3, limit pricing is sometimes used and sometimes successful. In E4, limit pricing is used, but to signal that the market is small rather than to conceal that it is large. These are, of course, the same equilibria that arose in the predatory pricing model, but the size of the parameter regions have changed. One difference is that in limit pricing, for given values of R_0, R_1, and R_2 there may be no values of θ and M that allow mixed signal jamming to be an equilibrium; region E3 may not exist. In addition, nonstrategic behavior is more attractive than in

[4]xxx I need to check this carefully.

Model I, because the condition for its optimality is now $M < R_2/R_1$ instead of the improbable $M < 2 - R_1/R_2$, which required $M < 2$. The size of M that makes signalling more attractive than mixed signal jamming has also changed, but it remains true that the attractiveness of mixed signal jamming increases in R_2 and decreases in R_0.

Proposition 1 says that there are four ways a rational incumbent might behave towards the rival, each appropriate to its own circumstances: (E1) to make no attempt to deter entry, (E2) to use signal-jamming, (E3) indifferently to use signal-jamming or accommodate, and (E4) to accommodate if the market is large and signal if the market is small. Equilibria E2 and E3 are similar to the signal jamming in Fudenberg & Tirole (1986) and Tirole (1988, p. 443), in which the incumbent conceals the size of the market by his action. In the original signal-jamming models, the incumbent himself does not know the size of the market. Here, he does, but the outcome is the same: the rival is forced to rely on data distorted by the incumbent. The incumbent's knowledge, however, makes possible equilibrium E4, equivalent to the separating equilibria in Milgrom & Roberts (1982a) and Roberts (1986), which does not exist under symmetric information. In E4, the incumbent reduces his profits not to conceal that the market is large, but to reveal that it is small. He is signalling that is he is not signal jamming.

The parameter regions in which these different strategies apply are defined by the monopoly profit premium and the probability of a small market. If the monopoly profit is small enough (region E1), strategic behavior is not worth the cost, whatever the probability of a small market. Even if the market is almost surely small, it is not worth pretending so, and the difference in profits between a small market and a large is unimportant. The condition that defines E1 is $M \leq 2 - \frac{R_1}{R_2}$, so the region can exist only if $M < 2$ and the product is differentiated enough that monopoly profits are less than twice duopoly profits. If monopoly profits are higher, then strategic behavior of various kinds becomes profitable. If the market is very probably small (region E2), then pure signal jamming is profitable, because it is not very difficult to persuade the rival to stay out. This is true even if acquiring a monopoly is extremely profitable, and the rival knows it is profitable, because he still views a low price as a reliable sign of a small market.

If a small market is less probable, however (regions E3 and E4), behavior becomes complicated. If monopoly profit is moderate (region E3), the equilibrium is in mixed strategies because unless the incumbent sometimes chooses a high price in a large market, a low price is not a credible indicator of a small market. True small markets are simply not common enough, so the rival is dubious and will sometimes enter even on observing a low price. If, however, monopoly profits are very high (region E4), then when the market is small it is so important to the incumbent to prevent entry that he is willing to take the extreme action R_0.

The signalling equilibrium is special because it can coexist with any of the three other equilibria and it requires careful specification of out-of-equilibrium beliefs. The incumbent chooses R_1 in neither a small nor a large market, and for this to be an equilibrium, the rival must believe that any incumbent who did choose R_1 was likely operating in large market. This is most plausible in parameter region E4, where the alternative to signalling is mixed signal jamming.

In other regions, the necessary out-of-equilibrium beliefs are less plausible, as the following two arguments show.

First, the signalling equilibrium is not robust to a small probability that the players are confused over which of the multiple equilibria is being played out. The incumbent moves first and prefers any of the other three equilibria to signalling except in region E4, and if such confusion were possible he could take advantage of it. Suppose, for example, that the parameters were located at point P_1 in Figure 1: a low monopoly premium and a large probability that the market is small. This is in region E1, so one equilibrium is nonstrategic, with $R_2|Large$ and $R_1|Small$, and another is signalling with $R_2|Large$, $R_0|Small$, and the out-of-equilibrium belief that $Prob(Large|R_1) = 1$. Such an out-of-equilibrium belief does not seem reasonable, because although R_1 is out-of-equilibrium behavior in the signalling equilibrium, it is equilibrium behavior in the nonstrategic equilibrium. If we relax slightly the standard assumption that the identity of the equilibrium to be played out is common knowledge, then if the rival thinks the equilibrium is signalling but observes R_1, he should wonder whether he and the incumbent might have conflicting notions of which equilibrium is being played out. It is equilibrium behavior for the incumbent to choose R_1 if the incumbent thinks the equilibrium is nonstrategic and the market is small, so, by this reasoning, the rival should believe that the market is indeed small on observing R_1. This breaks the signalling equilibrium. The same reasoning eliminates the signalling equilibrium in every other region except E4: if the rival interprets an action that is an equilibrium action in equilibrium Y as indicating that the equilibrium being played out by the other player is indeed Y, then the incumbent can effectively choose whichever equilibrium he prefers, and he will not choose the signalling equilibrium except in region E4.

Second, except in region E4 the signalling equilibrium is not robust to a small probability that the incumbent behaves nonstrategically. Assume that with probability η_1 the rival is informed of the market size and the incumbent receives a indicator to that effect, but he receives the same indicator with an additional probability η_2 when the rival is actually uninformed. Assume that η_2 is small enough that on receiving the indicator, the incumbent will find it optimal to behave nonstrategically. The incumbent will then sometimes play $R_1|Small$ in equilibrium, which rules out the signalling equilibrium in its pure-strategy form in every parameter region. In regions E1 and E2, the small-market incumbent will deviate to R_1, breaking the signalling equilibrium. In regions E3 and E4, both types of incumbents would deviate to R_1 to some extent, generating mixed-strategy equilibria. In region E3 this is simple enough, since the mixed-strategy equilibrium is close to the mixed signal-jamming described in Proposition 1. In region E4, the equilibrium involves a small amount of mixing but is essentially the same as the original signalling equilibrium. If the indicator is received, the incumbent will play $\{R_2|Large,\ R_1|Small\}$. If the indicator is not received, the incumbent's equilibrium strategy is $\{R_0|Small, R_1|Large$ with probability μ, $R_2|Large$ with probability $(1-\mu)\}$. The rival's equilibrium strategy is $\{In|Large,\ Out|Small\}$ if he is informed, and $\{Out|R_0,\ In|R_1$ with probability β, $Out|R_1$ with probability $(1-\beta)$, $In|R_2\}$ if he is uninformed. The values of β are the same as in the mixed signal-jamming equilibrium above.[5]

The value of μ must make the rival indifferent about entering when R_1 is observed. R_1 results from a small market and the indicator with probability $\theta\eta_2$, and from a deceptive large-market incumbent with probability $(1-\theta)\mu$. The rival's payoff is therefore

$$\pi(In|R_1) = \frac{\theta\eta_2}{\theta\eta_2 + (1-\theta)\mu}(R_1 - C) + \frac{(1-\theta)\mu}{\theta\eta_2 + (1-\theta)\mu}(R_2 - C). \qquad (9)$$

[5]xxx If the rival sees R_1, that could be because the incubment has gotten a mistaken indicator from Nature, and the true market is Small. Or i, it could be that the incumbent is uninfomred and bluffing.

Equating this to zero, the payoff from $Out|R_1$, and solving for μ gives

$$\mu = \frac{\theta\eta_2(C - R_1)}{(1-\theta)(R_2 - C)}. \tag{10}$$

For given θ, as η_2 goes to zero the equilibrium becomes arbitrarily close to the pure signalling equilibrium, because μ is small if η_2 is small, and if μ is small then R_1 is rarely chosen and the value of β rarely is relevant. Thus, a small probability that the incumbent is behaving nonstrategically eliminates the signalling equilibrium except in E4, and changes the equilibrium only slightly in E4 itself.

3. Interpretation

The first involves the strategic activity that generates low revenue. In both models, this can be interpreted as a low price, which reduces the revenue observed by the rival (his own in predatory pricing and the incumbent's in limit pricing). In limit pricing, another interpretation is that the strategic activity is low quality or advertising, which would also reduce the incumbent's revenue. This interpretation does not carry over comfortably to predatory pricing, because when both firms are in the market such activities may increase the rival's revenue at the same time as they reduce the incumbent's.[6]

Second, in limit pricing the incumbent may *expand* output, capacity, and price in the second period, after entry. That is because the incumbent's pre-entry action may have been devoted to keeping all of these variables small to make the market look unattractive to the rival. If the rival discovers the true state of the market after entry, the incumbent will give up concealment and maximize profits with abandon. This story, in fact, might explain the finding of Lieberman (1987) that entry into concentrated markets in the chemical industry was followed by incumbent expansion, unlike entry into unconcentrated markets.

Third, the limit pricing model provides an explanation for why monopolies might seem not to maximize profits. It explains apparently

[6]The same difference in interpretation exists, *a fortiori* between cost- based and demand-based limit pricing models. In a cost-based model, the incumbent uses low prices to indicate that he has low costs. If his low prices might be due to his own low quality, that just increases the rival's incentive to enter. In a demand-based model, the rival is interested in discovering market demand, something facing both firms, so low revenue can deter entry whether it is generated by an inappropriately low price or inappropriately low quality.

irrational actions, as an entry deterrence tactic: the monopoly deliberately reduces its profits to make the market unattractive. If entry occurs anyway, it will appear that competition has forced the monopoly to become more efficient, but what has happened is that it no longer worries about showing that high profits can be earned in this market.

Predation

The rival will not deviate from equilibrium, because the incumbent's choice fully reveals the type of market, and under the assumptions that $R_2 - C > 0$ and $R_1 - C < 0$, remaining in the market is only profitable if the market is large.

As in other models of predatory pricing, the incumbent is engaging in activities that make the market unprofitable to both the rival and himself, activities which the incumbent would cease if he thought the rival would not exit the market. Here, however, the incumbent is not threatening the rival, but confusing or warning him. In signal jamming, predatory pricing is profitable precisely because the rival does not know it is predatory. The incumbent does not need to make a threat of low prices credible, because he avoids making any threat, blaming low profits on the small size of the market. In signalling, on the other hand, the essence of the low price is that the rival knows it is a strategic signal indicating a small market. In both equilibria, the incumbent's present price is chosen to communicate something about the exogenous parameters, not something about the incumbent's future behavior.

This model of predation, unlike others, predicts that the incumbent will predate against rivals but rivals will not predate against the incumbent. In Telser's deep-purse model, it might well be the rival that has the deep purse— one thinks of chain stores predating against small grocery stores. In the Kreps-Wilson (1982) and Milgrom-Roberts (1982b) repeated-game models, the rival might pretend to be irrational or have low costs just as easily as the incumbent—or more easily, since the rival is less well-known. In the present model, it is key that one firm knows the market better than the other, and this is what makes it possible for the incumbent to predate.

Signalling Properties of the Model

Ordinarily, signalling models have three kinds of equilibria: separating equilibria in which only the desirable type signals, pooling equilibria in which neither type signals, and pooling equilibria in which both types signal. The desirable type prefers separation, the undesirable type prefers pooling with no signalling, and pooling with signalling is preferred by neither type. The pooling equilibria are vulnerable to elimination by various refinements of out-of-equilibrium beliefs because the desirable type has a strong incentive to separate out. In the present model, there is a separating equilibrium in which only the desirable type signals (E4), but also a pooling equilibrium in which only the undesirable type signals (E2). Moreover, both types of incumbent prefer pooling, when it exists as an equilibrium. The small-market incumbent has no incentive to separate out, because, thanks to the discreteness of entry, being pooled with the large-market incumbent has no ill consequences. Hence, the pooling equilibrium at R_1 is robust to out-of-equilibrium beliefs—more robust, in fact, than the separating equilibrium. This is why it is closer to signal jamming than to pooling in a standard signalling model. And this is why the arguments from small amounts of uncertainty over the equilibrium being played out and nonstrategic behavior make the signalling equilibrium implausible except in region E4.

It is natural to wonder whether allowing a continuum of signal levels instead of just three would matter. Suppose that if the market is large, the incumbent chooses $R \in (R_0, R_2]$, and if the market is small, the incumbent chooses $R \in [-\infty, R_1]$. If $R > R_1$, the rival deduces that the market is large. If $R \in (R_0, R_1]$, it is not clear what deduction should be drawn unless the level of R chosen is the level prescribed by the equilibrium, because out-of-equilibrium beliefs must be imposed by the modeller. There exists a continuum of pooling and separating equilibria, each enforced by the belief that the incumbent's deviation from the assigned R is a sign of a large market. The model with three levels of R strips this down to the revenue levels whose special properties do not depend on out-of-equilibrium beliefs: R_0 and R_2 definitely indicate the size of the market, and R_1 is the profit-maximizing revenue in the small market.[7]

It is also interesting to ask what happens when the model is modified so that no revenue level R_0 exists that unmistakably indicates a small market—effectively, $R_0 = -\infty$. No signalling equilibrium then exists, because even if the monopoly premium is large, the small-market incumbent

[7]The second refining principle described above also reduces the number of relevant revenue levels to these three, because R_1 could be used to indicate a small market if the equilibrium specified a smaller value for R.

will not attempt to reduce revenues to separate from the large-market incumbent because the large-market incumbent would be equally willing to reduce his profits in imitation. Region E3 increases to include E4, and even if the monopoly premium is large, signal jamming will occur.

The Literature

The most discussed kinds of entry deterrence are predatory pricing and limit pricing. Both practices involve a firm using a low price to keep competitors out of the market, but they differ in whether the competitors are initially in the market or not. In predatory pricing, a firm sets its price low in order to induce exit of an existing competitor. The predator's problem is to make credible its threat to keep the price low until the competitor exits, because the low price hurts itself as well as the victim. The threat might be credible because the victim has limited financial resources and cannot continue operating even though it knows that the predator will soon raise prices again— the "deep purse" theory of Telser (1967). Or, the incumbent might have a reputation to make or maintain, as in the reputation models of Kreps & Wilson (1982) and Milgrom & Roberts (1982b). The incumbent is willing to take losses because it can thereby successfully pretend to either be irrational or have low costs. In both stories, predation works by making an otherwise profitable market temporarily unprofitable. A third story can be based on the "signal jamming" model of Fudenberg & Tirole (1986). In this model of symmetric but imperfect information, an rival does not know whether it can operate profitably or not, because it is ignorant of its own fixed cost.[8] It enters and tries to use its profit to deduce the fixed cost, but profit also depends on the toughness with which the incumbent competes, which is unobserved. The incumbent may act as a tough competitor to induce the rival to exit under the belief that it is high fixed costs, not tough competition, that is responsible for low profits. The signal jamming model does not turn on the issue of credibility, because the victim does not know whether the incumbent is purposely reducing industry profits or not, and cannot predict an increase in profits after exit.

In limit pricing, a firm purposely reduces its profits—most simply by

[8] The assumption that the rival can observe its marginal but not its fixed cost is unrealistic, but it is useful for simplifying the model. If it were marginal cost that was unknown, then the rival's information would affect the output he chose; see Riordan (1985) for analysis of this effect.

not allowing its price to rise above a certain limit— in order to deter entry by firms not yet active in the market. The seminal modern limit-pricing model is Milgrom & Roberts (1982a), which explains limit pricing as signalling. The incumbent firm has high or low costs, known only to itself, and the rival does not wish to enter and compete with a low-cost incumbent. In the absence of possible entry, the low-cost incumbent would charge a lower price than the high-cost incumbent. But if entry is possible, the high-cost incumbent may wish to pretend that it is low-cost by charging less than the high-cost monopoly price. Or, if customers believe that high-cost firms might charge low prices the low-cost incumbent may need to reveal its identity by charging so low a price that imitation is unprofitable. Either way, some type of incumbent is using limit pricing.

The model of this paper bases the incumbent's behavior on the motive of trying to persuade the competitor, truthfully or deceitfully, that market demand is too weak for two firms to survive. The rival and incumbent are identical except that the incumbent is permanently in the market and knows the market size, but the rival must make its entry and exit decisions in ignorance. There are no entrance or exit fees, and no cost differences. The incumbent's tactic is to purposely depress profits, either to prevent profits from indicating the size of the market to the rival, a form of signal jamming, or to signal that the incumbent is not signal jamming. As in previous models, there are multiple equilibria, but arguments were made that for given parameter values the predicted equilibria should be unique (except for weak equilibria at boundaries), and that pooling equilibria, not just separating equilibria, should survive refinement. Besides showing that limit pricing and predatory pricing can have a common motivation, the model showed how the monopoly premium and rival beliefs influence whether the rival can be deterred, and how the incumbent may be driven to signalling that he is not signal jamming. Under some parameter values, the possibility of strategic behavior will hurt the incumbent, so that the idea that entry deterrence might be desirable to encourage innovation into entirely new markets will be invalid.

The model is similar in different ways to both Fudenberg & Tirole (1986) and Milgrom & Roberts (1982a), although those models are driven by uncertainty over costs rather than demand. Cost uncertainty is not unrealistic, but often what is most uncertain about a market is not individual firms' costs, but the common demand curve they face.[9] Demand may be even more important than costs to the profitability of entry. Strategic accommodation can permit a firm with higher costs to survive, but only in a large market can the rival enter at so small a scale as to make retaliation unprofitable for the incumbent, as Gelman & Salop (1983) suggest. Extensions of the Milgrom-Roberts (1982a) model to the case where the demand curve, not the cost curve, is private information have been made by Matthews & Mirman (1983), Roberts (1986), and Bagwell & Ramey (1990). In Matthews & Mirman (1983), the strength of demand is a continuous variable known to the incumbent but not the potential rival, who must estimate it by observing the market price. The market price, in turn, is based on a choice by the incumbent plus random noise. In equilibrium, incumbents in bigger markets choose higher prices, and the rival enters if the observed price is higher than a threshold level. Roberts (1986) is a predation model in which the predator has better information on demand than the victim and can choose output to induce the victim to believe that the market is small and exit. Under suitable assumptions on out-of-equilibrium beliefs, the equilibrium is a separating one in which the predator chooses a price lower than the monopoly level if demand is weak, and the victim exits. Bagwell & Ramey (1990) is a limit pricing model in which the incumbent has superior information on demand and can use both price and advertising levels to try to comunicate this to the rival. Refinements of equilibrium are explored, and the conclusion is that strategic behavior exaggerates the effects of demand differences. In general, these model predict separating equilibria, not pooling equilibria. The Fudenberg-Tirole signal-jamming model can also be extended to demand, and Tirole (1986, p. 443) shows how it might be based on differences in the general profitability of different markets when the incumbent can manipulate observed profitability even without knowing the true size of the market.

The entry deterrence tactic at the heart of the present model is signal jamming in the sense that one type of incumbent takes a costly action to block information that would reach the rival in the absence of strategic behavior. Fudenberg & Tirole use the term "signal jamming" because the

[9] There may also be uncertainty over common components of cost; see Harrington (1986) for a signalling model in which this is true. Entry deterrence can then take the form of charging a high price, not a low price, to indicate that the common costs are high.

incumbent is trying to prevent information from reaching the rival, rather than to communicate information, as in standard signalling. One type of incumbent has that same motivation in the pooling equilibrium of a signalling model, but Fudenberg and Tirole use a model of symmetric information, where the incumbent's action does not depend on type. The present model has incomplete information, and signal jamming will amount to one type taking a costly action to pool with another type. As will be seen, the properties of such pooling are closer to symmetric-information signal-jamming than to the pooling equilibrium of educational signalling, in which either zero or all types take a costly action.[10] Signalling will also occur in the model, however, because the incumbent sometimes wishes to signal that it is not signal jamming. This feature of the model will be closer to the results of Milgrom and Roberts than to Fudenberg and Tirole.

4. Model II : Innovative Entry and Limit Pricing

We usually consider strategic entry deterrence a bad thing, resulting in monopolies where there would otherwise be competitive markets, but the choice might actually be between a monopolized market and no provision of the good at all. It may be that the incumbent has innovated by discovering a profitable market niche and the rival is trying to seize some of the profits. The present model focusses on small markets, which might be able to contain only one firm, so it seems especially appropriate for looking at innovative markets: small monopolies that sell innovative products or sell in geographically restricted markets. This is a model of a doctor in a small town, not an automaker in a large country.[11] Moreover, small markets are a natural setting for information-based models, because information acquisition is subject to economies of scale and may be prohibitively costly for a small market. Thus, the implicit assumption that uninformed players will not simply buy the information they need is plausible.

It is a general feature of innovative markets that monopoly profits may be a socially desirable spur to entry, since a monopoly is better than no

[10] Some people prefer to use "signal jamming," to describe symmetric-information models or models in which the signal observed by the rival is a noisy function of the incumbent's behavior, instead of the deterministic function here. The use of the term in this paper emphasizes the intentional and costly blocking of information rather than symmetry of information or the presence of noise.

[11] For an analysis of prices in such markets, see Bresnahan & Reiss (1991) on concentration in small-town markets for services such as auto dealing and veterinary medicine.

seller at all. This, of course, is the rationale behind patents, and Hausman & Mackie-Mason (1988) point out, for example, that policy should encourage price discrimination in innovative markets to encourage entry. Could limit pricing be useful in the same way? It prevents the rival from free-riding on the incumbent's costly acquisition of the information that the market is not tiny, acquisition which may be costly either because of a fixed cost of research or because of the risk of failed entry. Model III will investigate whether monopoly-facilitating practices do encourage innovation in the present context. It extends Model II to the incumbent's original decision of whether to become the first firm in the market, given that the market might be too small to generate positive profits even for a monopoly. The market will now be tiny (profitable under no circumstances), small (profitable for one firm), or large (profitable for two firms). Either limit pricing or signal jamming could be used; the model below assumes that the rival can observe incumbent profits, so limit pricing is the relevant tactic. Let revenue in the tiny market be $R_{00} < R_0$, where $MR_{00} - C < 0$.

The Order of Play in Model II

1. Nature chooses the market to be *Tiny* with probability γ, *Small* with probability $(1-\gamma)\theta$ and *Large* with probability $(1-\gamma)(1-\theta)$, observed by neither player.

2. The incumbent decides whether to *Stay Out*, ending the game, or *Enter*. The incumbent observes the market size and chooses first-period revenue to be R_{00} if the market is tiny, R_0 or R_1 if it is small, and R_1 or R_2 if it is large, observed by the rival.

3. The incumbent chooses *Exit*, ending the game, or *Stay In*.

4. The rival decides whether to be *In* or *Out* for the second period.

5. The incumbent chooses revenue to be R_{00} if the market is tiny, R_0 or R_1 if it is small, and R_1 or R_2 if it is large, observed by the rival.

6. The incumbent and rival collect their second-period profits, which equal $R - C$ apiece if both are in the market, and $MR - C$ and 0 if the incumbent is alone.

Let us denote by π the incumbent's equilibrium profits in the ensuing subgame if the market is not tiny and he remains in after entering. The incumbent's payoff for the entire game is either

$$\pi_{Stay\ Out} = 0 \tag{11}$$

or

$$\pi Enter = \gamma(R_{00} - C) + (1 - \gamma)\pi. \tag{12}$$

Only if γ falls below a certain critical level γ^* will the incumbent be willing to enter. γ^* is found by equating (11) and (12):

$$\gamma^* = \frac{\pi}{\pi - (R_{00} - C)}. \tag{13}$$

If subgame profits increase, the critical level falls and the incumbent is willing to enter markets that have a higher probability of being tiny:

$$\frac{\partial \gamma^*}{\partial \pi} = -\frac{R_{00} - C}{(\pi - (R_{00} - C))^2} > 0, \tag{14}$$

where the inequality is true because $R_{00} - C < 0$. Hence, the question of whether strategic entry deterrence encourages innovation is the same as the question of how it affects π. Proposition 3 compares the incentive of the incumbent to enter when limit pricing is possible compared to when the rival can discover the true state of the market regardless of the incumbent's actions.

PROPOSITION 2: Pure signal jamming encourages innovation, but mixed signal jamming or signalling discourages it.

PROOF: If the subgame equilibrium is pure signal-jamming, the subgame profit is

$$\pi(LP) = (MR_1 - C) + \theta(MR_1 - C) + (1 - \theta)(MR_2 - C), \tag{15}$$

whereas if the rival could observe the market's profitability directly, the incumbent's subgame profit would be

$$\pi(no\ LP) = \theta(MR_1 - C) + (1 - \theta)(MR_2 - C) + \theta(MR_1 - C) + (1 - \theta)(R_2 - C). \tag{16}$$

The difference is

$$\pi(LP) - \pi(no\ LP) = (1 - \theta)(MR_1 - R_2) \geq 0, \tag{17}$$

where the inequality follows from condition (2), which holds whenever pure signal-jamming is an equilibrium. Since $\frac{\partial \gamma^*}{\partial \pi} > 0$, there are thus values of γ

for which the difference between these two profits makes the difference as to whether the incumbent enters, and limit pricing encourages the incumbent's initial entry.

If the equilibrium is mixed signal-jamming, the incumbent's two pure-strategy payoffs are equal, so we can use either one to represent the limit-pricing subgame profit. The overall subgame payoff across both sizes of markets, using the payoff from $R_2|Large$, is

$$\begin{aligned}\pi(LP) = \; & [\theta(MR_1 - C) + (1-\theta)(MR_2 - C)] + [\theta\beta(R_1 - C)+ \\ & \theta(1-\beta)(MR_1 - C) + (1-\theta)(R_2 - C],\end{aligned} \tag{18}$$

whereas if the rival can observe the market's profitability directly, the incumbent's subgame profits are as shown in equation (16). The difference is

$$\pi(LP) - \pi(no\ LP) = -\theta\beta(M-1)R_1, \tag{19}$$

which is negative. Limit pricing hurts the incumbent's profits and deters his entry. Similarly, if the equilibrium is signalling, the incumbent's profits are

$$\pi(LP) = [\theta(MR_0 - C) + (1-\theta)(MR_2 - C)] + [\theta(MR_1 - C) + (1-\theta)(R_2 - C)]. \tag{20}$$

The difference between this and the profit under full information is

$$\pi(LP) - \pi(no\ LP) = -\theta M(R_1 - R_0), \tag{21}$$

which is negative. Under signalling, the possibility of limit pricing hurts the incumbent's profits and deters his initial entry.□

Thus, to the well-known idea that monopoly-facilitating tactics can stimulate innovation by increasing profits is added a new idea: the same tactics can discourage innovation by reducing profits, because the rival is suspicious and makes mistakes. Under mixed signal jamming, he knows that the incumbent often is pretending that a large market is small, so he enters randomly— sometimes into a small market, driving the incumbent's profit negative. Under signalling, the underlying problem is still mistaken entry, but it has become so costly that costly signalling is the preferred response. If it were common knowledge that the market were small or that limit pricing was not being carried out, on the other hand, the worst the incumbent could do would be a small positive profit. The incumbent would like to be able to commit not to manipulate revenue, since effective communication of the market size increases his profits on average.

5. Conclusion

An incumbent firm can use low prices to communicate information about the size of the market in several different ways, ways that apply whether its competitor is already in the market (predatory pricing) or has not yet entered (limit pricing). Milgrom & Roberts (1982a) and its successors suggest that the incumbent might use low prices in separating equilibria to credibly indicate that the market is unprofitable and deter entry that would hurt both firms, or use moderate prices in a pooling equilibrium to cloud the market's profitability. Signal-jamming models in the tradition of Fudenberg & Tirole (1986) show that the incumbent might use low prices in pure or mixed-strategy pooling equilibria to similarly obscure the profitability of the market and perhaps deter entry, but without out-of-equilibrium beliefs being relevant. The model here, based on one firm's uncertainty over whether market demand is sufficiently strong to accommodate two firms, combines the two ideas. If it is required that the equilibrium be robust to uncertainty over which equilibrium is being played out or to the possibility of nonstrategic behavior, then the equilibrium is unique for given parameters, and it may be a pooling equilibrium that survives. If the prior belief is that the market is small, or if the premium from being a monopoly takes a low value, the incumbent will use signal jamming to prevent the rival from learning the true state of the market. Mixed-strategy signal jamming is costly, however, since it sometimes results in two firms mistakenly occupying a small market. Therefore, if the monopoly premium and the prior probability of a large market are big enough, the incumbent will resort to true signalling reminiscent of the separating equilibrium in Milgrom & Roberts (1982a): reducing profits to a level so low that it is clear the market must be small. This is defensive signalling: signalling that the incumbent is not signal jamming.

The model applies to small markets, where there is a strong possibility that the minimum efficient scale will only allow one firm to operate profitably. This suggests that the possibility of strategic behavior would influence whether even one firm dares enter the market. Entry into a virgin market is a form of innovation, and like other kinds of unpatentable discoveries, the discovery of a new market is prone to free-riding by other firms. One might think that the possibility of strategic behavior would act like a patent and eliminate the free-riding problem at some small cost by allowing the incumbent to monopolize the new market. When the prior probability that the new market can contain only one firm profitably is high, this is indeed the case, and the pure signal jamming that results encourages innovation. When the prior is low, however, strategic behavior is costly compared to honest disclosure of the market size, and both signalling and mixed signal jamming reduce innovation.

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