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Uncovering Entry Deterrence in the Presence of Learning-by-Doing

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Uncovering Entry Deterrence in the Presence of Learning-by-Doing*

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Abstract

This paper investigates a signaling entry deterrence model under learning-by-doing. We show that a monopolist's practice of entry deterrence imposes smaller welfare losses (or larger welfare gains) when learning effects are present than when they are absent, making the intervention of antitrust authorities less urgent. If, however, the welfare loss associated to entry deterrence is still significant, and thus intervention is needed, our paper demonstrates that the incumbent's practice of entry deterrence is easier to detect by a regulator who does not have access to accurate information about the incumbent's profit function. Learning-by-doing hence facilitates the regulator's ability to detect entry deterrence, thus suggesting its role as an "ally" of antitrust authorities.

KEYWORDS: Learning-by-doing; Entry deterrence; Incomplete information; Spillovers.
JEL CLASSIFICATION: L12, D82, D83.

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1 Introduction

Learning-by-doing has been empirically observed in multiple industries, such as aircraft manufacturing, shipbuilders, automobiles, and more recently, in the production of semiconductor memory chips, cable TV markets and health care.[1] The effect of learning-by-doing on firms' limit pricing practices has not been theoretically studied. However, entry deterrence has been empirically found in industries that are particularly characterized by significant learning-by-doing effects, such as cable TV markets, Seamans (2010), and health-care, Dafny (2005). Learning effects are especially relevant for the regulator. Indeed, distinguishing whether a firm's increase in production was due to entry-deterrence motives or to benefit from learning-by-doing was a key issue in policy debates about the "semiconductor wars" between the U.S. and Japan during the 1970s and 1980s; see Flamm (1993 and 1996). In this context, our paper shows that, rather than hindering the ability of the regulator to identify the practice of limit pricing, learning-by-doing can facilitate such a task.

Our paper investigates entry deterrence in industries where firms benefit from learning-by-doing and analyzes its welfare implications. We argue that the regulation of an incumbent practicing limit pricing becomes less urgent in terms of social welfare when industries benefit from learning-by-doing. In particular, this occurs because the inefficient type of incumbent raises its production during both periods in order to mimic the efficient type but also to benefit from learning. Hence, learning-by-doing raises consumer surplus not only in the first but in the second period, and as a consequence the practice of limit pricing imposes a smaller welfare loss (or a larger welfare gain) when learning effects are present. Therefore, from a regulatory viewpoint, our findings suggest that the prohibition of limit pricing becomes less necessary when learning effects are large.

If the welfare loss associated to entry deterrence is significant, intervention by antitrust authorities might still be necessary. In such case, we demonstrate that entry deterrence becomes easier to detect by the regulator when learning effects are present. Specifically, this occurs because the difference between the first-period output that the inefficient incumbent selects under incomplete information —deterring entry in the market— and that under complete information —attracting entry— expands as learning becomes more significant. The enlarging wedge between these two output levels is especially useful for regulators holding inaccurate information about the incumbent's profit function, since authorities cannot perfectly predict their true values, but only confidence intervals around them. The lack of accurate information can be particularly problematic when learning effects are absent. In such context, these output levels are potentially close to each other, implying that the regulator's confidence intervals can overlap, limiting its ability to identify whether the incumbent is practicing limit pricing. If, in contrast, learning effects exist, these two output levels are more distant from each other, reducing the potential for overlapping, which allows antitrust authorities to more easily detect and prove limit pricing. This result highlights the role

[1] After the initial study by Wright (1936), who documented learning effects on the aircraft manufacturing industry, multiple studies followed, such as Lane (1951) for shipbuilders, Hirsh (1952) and Baloff (1966) for machine manufacturing, White (1977) for automobiles and, more recently, Gruber (1992) and Siebert (2010) for the production of semiconductor memory chips, Gillett et. al. (2006) for cable TV markets and Waldman et al. (2003) for health care.

of learning-by-doing as an "ally" of the regulator. Because learning effects can be expected to become more significant in several technological industries —such as semiconductor memory chips, as documented by Gruber (1992) and Siebert (2010)— and in the compliance of environmental regulation —as shown by Monty (1991) and Dean and Brown (1995)— an understanding of this role is both important and timely.

Our paper builds upon the literature on entry deterrence in signaling games, such as Milgrom and Roberts (1982) and Matthews and Mirman (1983).[2] Usual entry deterrence models, however, assume that the incumbent's first-period action (e.g., price setting by a monopolist) does not affect incumbent and entrant's future profits. In our model, in contrast, the incumbent's first-period output reduces its future costs, thus increasing its second-period profits and decreasing the entrant's.[3]

In addition, our paper extends the literature on learning-by-doing by introducing *asymmetric* information and signaling in an entry deterrence model. This literature, initiated by Spence (1981) and Fudenberg and Tirole (1983) with models of complete information,[4] was afterwards extended to a context of symmetric incomplete information by Cabral and Riordan (1997), who analyze the welfare consequences of predatory pricing in a setting of two firms initially competing in the same market. In particular, both firms initially active in the industry cannot observe the fixed cost K that one of the firms must incur in order to remain active in the future, but observe its probability distribution, i.e., firms are symmetrically uninformed. Both firms afterwards observe the realization of the fixed cost K. Our paper identifies, however, an advantage of learning-by-doing that previous papers in the literature did not consider, namely, facilitating the detection of entry deterrence practices. In a recent article, Yang (2010) also examines the effect of learning in a limit-pricing model. Despite the similarities, our paper differ along several dimensions: first, we allow for general profits functions (only considering linear demand in our parametric example); second, we explicitly analyze how entry-deterrence practices are affected by learning (and therefore how easy they are to be detected by uninformed regulators); finally, we investigate the effect of allowing for learning spillovers (diffusion in learning).

Section two describes the model and section three analyzes the signaling game under learning-by-doing. We develop a parametric example similar to that in Fudenberg and Tirole (1983) and Cabral and Riordan (1997), in order to enhance the intuition behind the main results. Section four discusses the implications of our findings in terms of welfare and antitrust policy and examine the case in which learning spillovers exist. Finally, section five concludes.

[2] Harrington (1986) modifies Milgrom and Roberts' (1982) model by allowing the possibility that the entrant is uncertain about its own costs after entry. Interestingly, he shows that when the entrant's and the incumbent's costs are sufficiently positively correlated then Milgrom and Roberts' (1982) results are reversed. That is, the incumbent's production is below the simple monopoly output in order to strategically deter entry.

[3] Papers studying incomplete information settings where the incumbent's first-period action affects its future profits include Bagwell and Ramey (1990), where firms use advertising to signal their type, and Brander and Lewis (1986), where firms use debt as a signal.

[4] Other theoretical studies assuming complete information include Petrakis, Rasmusen and Roy (1997), Dasgupta and Stiglitz (1988), Cabral and Riordan (1994) and Hollis (2002). For a recent survey of the literature see Thompson (2008).

2 Model

Consider an entry game with an incumbent (Firm 1) monopolist and an entrant (Firm 2) who analyzes whether or not to join the market. The incumbent's marginal costs are either high H or low L, i.e., $c_1^H > c_1^L > 0$. We first examine the case where entrant and incumbent are informed about each others' marginal costs, and afterwards the case in which the entrant is uninformed about the incumbent's costs. Let us consider a two-stage game where, in the first stage, the incumbent has monopoly power and selects an output level q. In the second stage a potential entrant decides whether or not to enter. If entry occurs, agents compete as Cournot duopolists, simultaneously selecting production levels x_1 and x_2, for the incumbent and entrant, respectively. Otherwise, the incumbent maintains its monopoly power during both periods.

During the second period, if entry does not occur, the incumbent chooses output x_1 which maximizes monopoly profits

$$\overline{M}_1^K(q) \equiv \max_{x_1} p\left(x_1\right) x_1 - \bar{c}_1^K(q)x_1,$$

where $x_1^{K,m}(q)$ is the profit-maximizing second-period output and $K = \{H, L\}$. The inverse demand function $p(\cdot)$ is decreasing and concave in output, satisfies $p(0) \geq c_1^K$, and is constant across periods. The incumbent's second-period marginal costs $\bar{c}_1^K(q)$ are weakly decreasing in first-period output q, reflecting the presence of learning-by-doing across periods. For simplicity, we consider that learning-by-doing exhibits diminishing returns, i.e., $\bar{c}_1^K(q)$ decreases in q but at a decreasing rate.[5] If entry occurs, firms compete as Cournot duopolists in the second period, with associated equilibrium profits for the incumbent and entrant respectively,

$$D_1^K(q) \equiv \max_{x_1} p\left(X\right) x_1 - \bar{c}_1^K(q)x_1 \quad \text{and} \quad D_2^K(q) \equiv \max_{x_2} p\left(X\right) x_2 - c_2 x_2 - F$$

where X denotes aggregate second-period equilibrium output, $\bar{c}_1^K(q) < c_1^K$ for all $q > 0$, $c_2 = c_1^H$ represents the entrant's marginal cost, and F denotes the fixed entry cost. To make the entry decision interesting, assume that when the incumbent's costs are low, entry is unprofitable, whereas when they are high entry is profitable, i.e., $D_2^L(q) < 0 < D_2^H(q)$ for all q.[6]

First period, No entry. When the incumbent's costs are low, entry does not occur. Hence, the incumbent chooses a first-period output q that solves

$$\max_{q} \; p(q)q - c_1^L q + \delta \overline{M}_1^L(q),$$

where $\delta \in (0, 1)$ denotes the incumbent's discount factor. A marginal increase in first-period

[5] Note that this allows for both linear and convex learning curves. For simplicity, we consider that the learning curve of the high-cost incumbent lies above that of the low-cost firm, which rules out that an initially inefficient incumbent becomes the efficient firm in the second period through learning.

[6] The incumbent's capacity is hence limited, since the high-cost incumbent cannot produce a sufficiently large amount during the first period in order to blockade entry, thus eliminating the informative role of first-period output.

output not only produces an increase in marginal revenue but also raises second-period profits provided the cost-reduction effect associated to learning.[7] Let $q^{L,NE}$ denote the solution to the above maximization problem with low costs, where NE represents that no entry occurs.

First period, Entry. When the incumbent's costs are high, entry follows in the second period. Hence, the incumbent chooses a first-period output q that solves

$$\max_{q} \;\; p(q)q - c_1^H q + \delta D_1^H(q).$$

In this case a marginal increase in first-period output produces not only a cost-reduction effect but also a strategic effect since the entrant reduces its duopoly output when facing a more competitive incumbent.[8] Let $q^{H,E}$ denote the solution to the above maximization problem with high costs, where the superscript E represents entry.

Example. Considering a linear inverse demand function $p(q) = 1 - q$ and no discounting, $\delta = 1$. The incumbent's marginal costs satisfy $1 > c_1^H > c_1^L$. In the second period, the incumbent's marginal costs, $\overline{c}_1^K(q) = c_1^K - \lambda q$, decrease in learning-by-doing, where $\lambda > 0$ denotes the learning factor and $K = \{H, L\}$. When no entry occurs, the incumbent selects output $x_1^{K,m}(q) = \frac{1-(c_1^K - \lambda q)}{2}$ and $q_1^{K,NE} = \frac{(1-c_1^K)(2+\lambda)}{4-\lambda^2}$ in the second and first period, respectively, both being increasing in learning. When entry occurs, incumbent and entrant choose $x_1^{K,d}(q) = \frac{1+c_2-2(c_1^K-\lambda q)}{3}$ and $x_2^{K,d}(q) = \frac{1-2c_2+(c_1^K-\lambda q)}{3}$ in the second period,[9] while the incumbent selects $q^{K,E} = \frac{9+4(1-c_2)\lambda - c_1^K(9+\lambda)}{18-8\lambda^2}$ in the first period.[10] Finally, when learning is absent, $\lambda = 0$, second-period output coincides with that in the single-period duopoly game, $x_1^{K,d} = \frac{1+c_2-2c_1^K}{3}$ and $x_2^{K,d} = \frac{1-2c_2+c_1^K}{3}$, while the incumbent's first-period output becomes $q_{monop}^K = \frac{1-c_1^K}{2}$.

3 Signaling game

In this section we investigate the case where the incumbent is privately informed about its marginal costs, while the entrant only observes the incumbent's first-period output. The time structure of this signaling game is as follows.

1. Nature decides the realization of the incumbent's marginal costs, either high or low, with probabilities $p \in (0, 1)$ and $1 - p$, respectively. The incumbent privately observes this realization but the entrant does not.

[7] Note that the sum of these two benefits is decreasing in q, provided that the inverse demand function is concave in output and learning-by-doing exhibits diminishing returns. That is, further increases in first-period output induce a decreasing marginal benefit across periods.

[8] We consider, for simplicity, that a given reduction in second-period costs produces a larger increase in the incumbent's profits when it maintains its monopoly power than when entry follows. This condition holds for most parameter values under linear demand, as in the parametric example developed throughout the paper.

[9] Both firms produce non-negative second-period output as long as learning is not extremelly high, i.e., $\lambda \leq \frac{1-2c_2+c_1^K}{q^K}$.

[10] Note that the second-order conditions for the incumbent's first-period profit-maximization problem requires $\lambda^2 < 9/4$.

2. The incumbent chooses its first-period output level, q.

3. Observing the incumbent's output decision, the entrant forms beliefs about the incumbent's initial marginal costs. Let $\mu(c_1^H|q)$ denote the entrant's posterior belief about the initial costs being high after observing a particular first-period output from the incumbent q.

4. Given the above beliefs, the entrant decides whether or not to enter the industry.

5. If entry does not occur, the incumbent maintains its monopoly power, whereas if entry occurs, both agents compete as Cournot duopolists and the entrant observes the incumbent's type.[11]

3.1 Separating equilibrium

Let us next analyze the separating equilibrium where the incumbent selects a first-period output q^H when its costs are high, but chooses q^L when its costs are low.[12] Entrant's equilibrium beliefs after observing equilibrium output q^H and q^L are $\mu(c_1^H|q^H) = 1$ and $\mu(c_1^H|q^L) = 0$, respectively. The entrant enters (stays out) when it infers that the incumbent's initial cost are high (low, respectively). First, we investigate the conditions that guarantee the existence of a separating equilibrium. When its marginal costs are high, the incumbent selects the first-period output that maximizes its profits across both periods given that entry occurs, $q^{H,E}$. If the incumbent deviates towards the low-cost incumbent's output q^L, it deters entry. Hence, the high-cost incumbent selects its equilibrium output $q^{H,E}$ if $M_1^H(q^{H,E}) + \delta D_1^H(q^{H,E}) \geq M_1^H(q^L) + \delta \overline{M}_1^H(q^L)$ or equivalently,[13]

$$M_1^H(q^{H,E}) - M_1^H(q^L) \geq \delta \left[\overline{M}_1^H(q^L) - D_1^H(q^{H,E})\right] \tag{C1}$$

Likewise, if the low-cost incumbent chooses the equilibrium output q^L, it deters entry. If instead the incumbent deviates towards the high-cost incumbent's output, $q^{H,E}$, it attracts entry. Conditional on entry, the low-cost incumbent can select an off-the-equilibrium output $q^{L,E} \neq q^{H,E} \neq q^L$ which maximizes its profits, yielding $M_1^L(q^{L,E}) + \delta D_1^L(q^{L,E})$. Thus, the low-cost incumbent selects its equilibrium output of q^L if $M_1^L(q^L) + \delta \overline{M}_1^L(q^L) \geq M_1^L(q^{L,E}) + \delta D_1^L(q^{L,E})$, or equivalently,

$$M_1^L(q^{L,E}) - M_1^L(q^L) \leq \delta \left[\overline{M}_1^L(q^L) - D_1^L(q^{L,E})\right] \tag{C2}$$

The following proposition describes the only separating equilibrium of the signaling game that survives the Cho and Kreps' (1987) Intuitive Criterion.

Proposition 1. *A separating strategy profile can be sustained as a Perfect Bayesian Equilibria (PBE) in the signaling game where:*

[11] Note that if both firms continue their competition in future periods and both can benefit from learning-by-doing after becoming perfectly informed, then their output schedules would resemble those in Fudenberg and Tirole (1983).

[12] The separating output q^L is weakly higher than the production level that the low-cost incumbent selects under complete information, $q^{L,NE}$. Otherwise, the high-cost incumbent could be tempted to pool with the low-cost incumbent by selecting $q^{L,NE}$.

[13] Incentive compatibility condition C1 also guarantees that the high-cost incumbent does not have incentives to deviate towards any off-the-equilibrium output q such that $q \neq q^{H,E} \neq q^L$; see proof of Proposition 1.

1. *In the first period, the high-cost incumbent selects* $q^{H,E}$ *and the low-cost chooses* $q^L = q^A$*, where* q^A *solves conditions C1 with equality, respectively, and* $q^A > q^{L,NE}$*;*

2. *The entrant enters only after observing* $q^{H,E}$*, given equilibrium beliefs* $\mu(c_1^H|q^{H,E}) = 1$ *and* $\mu(c_1^H|q^A) = 0$*. For any off-the-equilibrium output level* q*, where* $q \neq q^{H,E} \neq q^A$*, entrant's beliefs are* $\mu(c_1^H|q) = 1$*, and prior probability* p *satisfies* $p > \overline{p}(q^{L,NE})$*, where* $\overline{p}(q^{L,NE}) \equiv \frac{-D_2^L(q^{L,NE})}{D_2^H(q^{L,NE})-D_2^L(q^{L,NE})}$*; and*

3. *In the second period of the game, the incumbent selects an output* $x_1^{K,m}(q)$ *if entry does not occur, and every firm* $i = \{1, 2\}$ *chooses* $x_i^{K,d}(q)$ *if entry occurs.*

Therefore the high-cost incumbent selects a first-period output $q^{H,E}$, which coincides with its output under complete information; while the low-cost incumbent chooses q^A, which is larger than its output under complete information, $q^{L,NE}$, in order to convey its cost structure to the entrant, deterring it from entering.

A sensible measure of the overproduction that the low-cost incumbent practices in order to convey its type to the potential entrant (and thus deter entry) is the distance between its output choices under incomplete and complete information, $q^A - q^{L,NE}$, i.e., its "separating effort." A natural question is whether the incumbent's separating effort increases in learning. To answer this question, note that learning produces two opposing effects. First, the incumbent's complete information output, $q^{L,NE}$, increases in learning, reducing the separating effort for a given q^A. Second, the benefits from deterring entry rise in learning,[14] entailing a larger separating effort, for a given $q^{L,NE}$. When the second effect dominates the first, a stronger separating result can be sustained under learning-by-doing. This occurs when returns from learning effects are relatively strong. For standard functional forms, such as those in our next example, as well as in Fudenberg and Tirole (1983) and Cabral and Riordan (1997), the separating effort is indeed increasing in learning. Intuitively, since the incentives to deter entry for both types of incumbent are increasing in learning, the low-cost incumbent is forced to enlarge the extent of its overproduction (i.e., its separating effort) in order to convey its type to the potential entrant.

Example. Continuing with our above example, and considering $c_1^H = \frac{1}{2}$ and $c_1^L = \frac{1}{3}$, the following figure compares the separation result in standard entry-deterrence models without learning, as in Milgrom and Roberts (1982), and the separating outcome under learning-by-doing described in Proposition 1. Under no learning-by-doing, $\lambda = 0$, the low-cost incumbent raises its first-period output from $q^L_{monop} = 0.33$ under complete information to $\widetilde{q}^A = 0.43$ under the separating equilibrium. Under learning by doing, e.g., $\lambda = \frac{1}{3}$, the low-cost incumbent increases its first-period output

[14] The fact that entry-deterrence benefits are increasing in learning can be confirmed by examining the right-hand side of expressions C1 and C2, which measure the different in the incumbent's monopoly and duopoly profits. Specifically, since $\overline{M}_1^K(q^L)$ is increasing and concave in q^L, whereas $D_1^K(q^{K,E})$ is constant, curve $\delta\left[\overline{M}_1^K(q^L) - D_1^K(q^{K,E})\right]$ is also increasing and concave in q^L for both types of incumbent. An increase in learning produces an increase in the positive slope of the curve.

from $q^{L,NE} = 0.4$ under complete information to $q^A = 0.81$ under the separating equilibrium, implying a larger separating effort.[15]

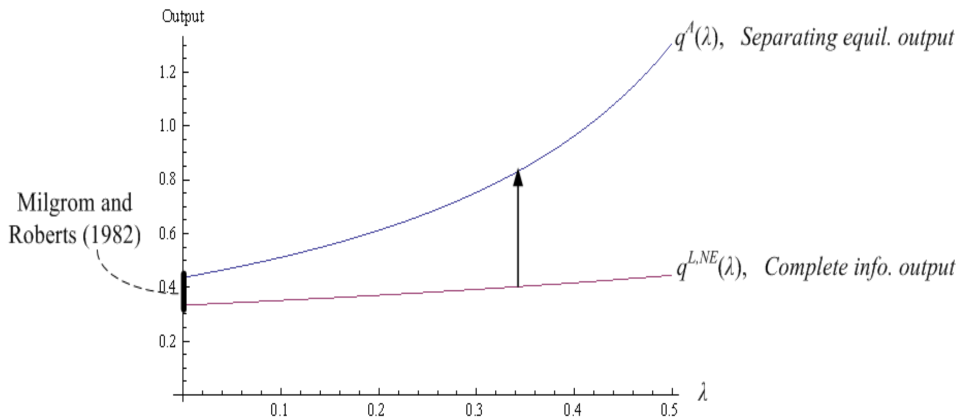

Fig. 1. "Separating effort" of the low-cost incumbent.

3.2 Pooling equilibrium

Let us describe the pooling equilibrium of the game, where both types of incumbent select the same first-period output.

Proposition 2. *The following strategy profile describes the pooling PBE in the entry deterrence game that survive the Cho and Kreps' (1987) Intuitive Criterion:*

1. *In the first period, both types of incumbent select the same first-period output* $q^{L,NE}$*;*
2. *The entrant does not enter after observing the equilibrium output* $q^{L,NE}$*, but enters after observing off-the-equilibrium output* q*,* $q \neq q^{L,NE}$*, given beliefs* $\mu(c_1^H|q^{L,NE}) = p < \overline{p}(q^{L,NE})$ *and* $\mu(c_1^H|q) = 1$*; and*
3. *In the second period of the game, the incumbent selects* $x_1^{K,m}(q)$ *if entry does not occur, and every firm* $i = \{1, 2\}$ *chooses* $x_i^{K,d}(q)$ *if entry occurs.*

Therefore, in the pooling equilibrium both types of incumbent produce the same first-period output, $q^{L,NE}$, which reveals no additional information to the entrant, thus deterring entry. Following the same example as in the separating equilibrium, figure 2 illustrates the increase in the high-cost incumbent's output, from $q^{H,E}$ under complete information to $q^{L,NE}$ in the pooling equilibrium, and

[15] Note that learning must be sufficiently low in order to guarantee that the entrant is willing to enter when the incumbent's costs are high. For the parameter values considered in the example, this implies that λ must be lower than 1/2. Otherwise, the inefficient incumbent could increase first-period output until a level that makes entry unprofitable, i.e., using first-period production to blockade entry. Such setting would eliminate, however, the informative role of first-period production in the signaling game.

how such increase grows in learning. For instance, $q^{L,NE} - q^{H,E}$ increases from $0.33 - 0.25 = 0.08$ when $\lambda = \frac{1}{100}$ to $0.49 - 0.33 = 0.16$ when $\lambda = \frac{1}{2}$. Intuitively, learning increases both types of incumbent's entry-deterrence benefits, thus raising the incentives of the high-cost incumbent to deter entry by mimicking the output level of the low-cost firm, i.e., overproducing.

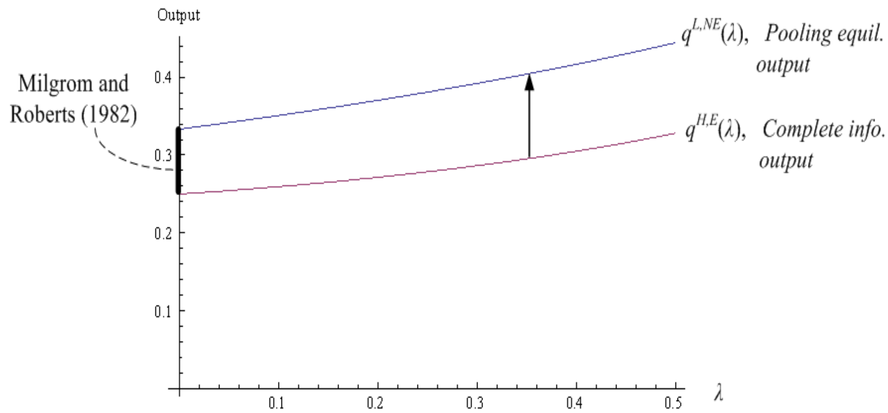

Fig. 2. Overproduction of the high-cost incumbent.

4 Discussion

Welfare comparison. Let us next evaluate social welfare under different degrees of learning in the *separating* equilibrium. When the incumbent's costs are high, output coincides with that under complete information, thus yielding the same welfare in both information contexts. When the incumbent's costs are low, in contrast, output schedules differ. In particular, first-period output is not only increased to benefit from learning (as under complete information), but also to deter entry, which further increases consumer surplus across both periods. Therefore, learning produces an increase in social welfare in the complete information setting, and this increase is emphasized in the separating equilibrium. The first column of the following table compares social welfare between the separating equilibrium and the complete information setting in our previous example. Further increases in learning emphasize the welfare advantage of the separating equilibrium.[16] Standard entry-deterrence models with signaling show that the incumbent's incentives to deter entry can actually improve social welfare relative to the complete information context. Our results hence suggest that such positive effect on welfare can be augmented as learning becomes more significant.

[16] Other parameter combinations produce similar welfare comparisons and can be provided by the authors upon request.

	Separating equil. vs. Complete Info	*Pooling equil. vs. Complete Info*
$\lambda = \frac{1}{100}$	0.031	0.002
$\lambda = \frac{1}{3}$	0.115	0.077
$\lambda = \frac{1}{2}$	0.177	0.127

Table I. Comparison of social welfare between incomplete and complete information

We next evaluate the welfare consequences of learning in the *pooling* equilibrium of the game. In the case of low costs, the incumbent produces the same output as under complete information and thus social welfare is unaffected by the information structure of the game. When costs are high, the incumbent selects a higher level of output, $q^{L,NE}$, than in the complete information setting, $q^{H,E}$, in order to deter entry. This increases consumer surplus during the first period, but reduces it during the second period since the high-cost incumbent maintains its monopoly power. On one hand, learning *increases* in the first-period welfare gain, since the high-cost incumbent produces more. On the other hand, learning *reduces* the second-period welfare loss, because a larger production in the first-period decreases the incumbent's second-period costs, leading to an increase in output. An increase in learning-by-doing therefore expands the set of parameter values under which the pooling equilibrium of the game is welfare improving, relative to complete information. The second column of Table I illustrates this result for different degrees of learning. From a regulatory standpoint, the high-cost incumbent's practice of limit pricing imposes a *smaller welfare loss* (or a larger welfare gain) when learning effects are present than when they are absent.[17]

Antitrust policy. In the case that both types of incumbent pool selecting the same first-period output level, $q^{L,NE}$, our results suggest that regulation becomes less urgent when learning effects are strong. Nonetheless, if the welfare loss associated to the pooling equilibrium is still significant, learning makes limit pricing by the high-cost incumbent more "visible" to antitrust authorities. In order to pool with the low-cost firm, the high-cost incumbent must raise its production from $q^{H,E}$ to $q^{L,NE}$, where the distance between these two output levels increases in learning. Importantly, a regulator who does not have access to accurate information about the incumbent's profits, might just have confidence intervals around the true value of $q^{H,E}$ and $q^{L,NE}$. If learning effects are small, these output levels are closer to each other, and hence confidence intervals could overlap, not allowing the regulator to identify whether the incumbent is producing its complete information output or if, instead, it is practicing limit pricing to deter potential entry. If learning effects are large, however, these confidence intervals are less likely to overlap since $q^{H,E}$ and $q^{L,NE}$ are further apart, permitting the antitrust authority to identify limit pricing. In summary, learning becomes

[17] This welfare analysis resembles that in Cabral and Riordan (1997), who consider predatory pricing between two firms initially competing in the same market. In particular, they show that predatory pricing can be welfare improving if the first-period welfare gain from a larger duopoly output offsets the second-period welfare loss from monopoly output. Similarly, in the pooling equilibrium of our model, we show that social welfare can actually increase relative to complete information.

an "ally" of antitrust authorities seeking to avoid entry deterrence.

Diffusion in learning. In certain contexts the incumbent's cumulative experience not only benefits itself but also the potential entrant.[18] In this case, first-period output still produces a cost-reducing effect, both under monopoly and duopoly. The incumbent's strategic effect, however, becomes smaller since the entrant does not reduce its duopoly output by the same amount as it did when learning effects accrued only to the incumbent. This implies that, under complete information, the low-cost incumbent still selects $q^{L,NE}$ since entry does not follow. In contrast, the high-cost incumbent's first-period output, $q^{H,E}$, decreases in the degree of diffusion, given that the incumbent's incentive to reduce its second-period costs decreases. The introduction of diffusion, hence, expands the wedge between $q^{L,NE}$ and $q^{H,E}$. As a consequence, diffusion reduces the amount of information that the regulator needs to detect the practice of limit pricing in the incomplete information setting.

5 Conclusions

This paper analyzes entry deterrence models where the incumbent benefits from learning-by-doing and holds private information about its efficiency level. We show that a monopolist's practice of entry deterrence imposes smaller welfare losses (or larger welfare gains) when learning effects are present, making the intervention of antitrust authorities less urgent. If, however, the welfare loss associated to entry deterrence is still large —calling for the need of intervention— our paper demonstrates that the incumbent's practice of entry deterrence is easier to detect by the regulator, i.e., learning-by-doing becomes an "ally" of antitrust authorities. We then extend our results to the case in which learning spillovers (diffusion) exits, showing that, under relatively general conditions, our previous results are emphasized as diffusion increases.

Note that, for simplicity, we consider that incumbent's and entrant's costs are uncorrelated. In certain industries, nonetheless, costs may be positively, as described in Harrington (1986). Under no learning, the incentives of the efficient incumbent to overproduce in order to reveal its low cost are diminished. However, with learning-by-doing those results could reversed since overproduction in the first period generates a cost advantage to the incumbent in the second-period game.

Finally, this paper considers a single entrant in a two-period model. Another venue of future research is to allow for multiple entrants who sequentially choose whether to enter the industry. If entrants are symmetric, the incumbent's cost advantage increases as its production accumulates over time, i.e., the incumbent moves down its learning curve, supporting our entry-deterrence result under larger parameter conditions. Once such significant entry barriers have been built, entry is

[18] For empirical studies documenting diffusion in learning see Irwin and Klenow (1994) in semiconductors, Lieberman (1989) in chemicals and Foster and Rosenzweig (1995) in the adoption of high-yielding seed varieties. Many empirical studies testing the presence of learning spillovers, however, have been controversial because of using industry-wide as a proxy for firm-specific cumulative output; see Thompson (2008). Nonetheless and for completeness we analyze diffusion in learning.

not socially optimal, even if the incumbent was initially inefficient, and regulation could be directed towards pricing strategies given the incumbent's monopolization of the market.

6 Appendix

6.1 Appendix 1

Let us investigate the conditions under which $\delta\left[\bar{M}_1^L(q^L) - D_1^L(q^{L,E})\right]$ is above $\delta\left[\bar{M}_1^H(q^L) - D_1^H(q^{H,E})\right]$. For compactness, let $\overline{M}_1(q,c_1)$ denote monopoly second-period equilibrium profits as a function of first-period output, q, and the incumbent's initial marginal cost, c_1. Similarly, let $D_1(q^E(c_1),c_1)$ represent duopoly second-period equilibrium profits as a function of the first-period equilibrium output that maximizes the incumbent's profits given that entry follows, $q^E(c_1)$. Hence, we next show that the difference $\overline{M}_1(q,c_1) - D_1(q^E(c_1),c_1)$ is decreasing in the initial cost c_1. In particular, differentiating with respect to c_1 and using the envelope theorem, we obtain

$$-\frac{\partial\overline{c_1}(q,c_1)}{\partial c_1}x_1^m(q,c_1) - \left[\frac{\partial p\left(x_1^d(q,c_1),x_2^d(q,c_1)\right)}{\partial x_2^d}\frac{\partial x_2^d(q,c_1)}{\partial\overline{c_1}}\frac{\partial\overline{c_1}(q,c_1)}{\partial c_1}\right. \tag{A.1}$$

$$\left.-\left(\frac{\partial\overline{c_1}(q^E(c_1),c_1)}{\partial q}\frac{\partial q^E(c_1)}{\partial c_1} + \frac{\partial\overline{c_1}(q^E(c_1),c_1)}{\partial c_1}\right)\right]x_1^d(q,c_1) \leq 0$$

Note that if learning-by-doing is absent, then $\frac{\partial\overline{c_1}(q^E(c_1),c_1)}{\partial q^E(c_1)} = 0$ and $\frac{\partial\overline{c_1}(q,c_1)}{\partial c_1} = \frac{\partial\overline{c_1}(q^E(c_1),c_1)}{\partial c_1} = 1$, and the above condition A.1 is negative if

$$-\left[x_1^m(q,c_1) - x_1^d(q,c_1)\right] - \left[\frac{\partial p\left(x_1^d(q,c_1),x_2^d(q,c_1)\right)}{\partial x_2^d}\frac{\partial x_2^d(q,c_1)}{\partial\overline{c_1}}\right]x_1^d(q,c_1) \leq 0 \tag{A.2}$$

where the first term is negative given that $x_1^m(q,c_1) > x_1^d(q,c_1)$ for a given q and c_1, and the second term is positive given that $\frac{\partial p\left(x_1^d(q,c_1),x_2^d(q,c_1)\right)}{\partial x_2^d} < 0$ and $\frac{\partial x_2^d(q,c_1)}{\partial\overline{c_1}} > 0$. Hence, condition A.2 holds as long as the inverse demand function is relatively insensitive to increases in output (elastic), i.e., $-\left[\frac{\partial p\left(x_1^d(q,c_1),x_2^d(q,c_1)\right)}{\partial x_2^d}\frac{\partial x_2^d(q,c_1)}{\partial\overline{c_1}} - 1\right] \leq \frac{x_1^m(q,c_1)}{x_1^d(q,c_1)}$. Provided that condition A.2 holds, A.1 is also satisfied if, in addition, $\frac{\partial\overline{c_1}(q^E(c_1),c_1)}{\partial q}\frac{\partial q^E(c_1)}{\partial c_1} > 0$ is relatively small.

Finally, note that the positive slope of $\delta\left[\overline{M}_1^H(q^L) - D_1^H(q^{H,E})\right]$ is $-\frac{\partial\overline{c_1}^H(q)}{\partial q}x_1^{H,m}(q)$, which is lower than that of $\delta\left[\overline{M}_1^L(q^L) - D_1^L(q^{L,E})\right]$, $-\frac{\partial\overline{c_1}^L(q)}{\partial q}x_1^{L,m}(q)$. Therefore, curve $\delta\left[\overline{M}_1^H(q^L) - D_1^H(q^{H,E})\right]$ is flatter than $\delta\left[\overline{M}_1^L(q^L) - D_1^L(q^{L,E})\right]$, guaranteeing that the former does not cross the latter. ■

6.2 Appendix 2 - Single Crossing Condition

Lemma A. *The incumbent's profits satisfy the single-crossing property under all parameter values when entry does not occur. When entry occurs, the single-crossing property holds if* $\frac{\partial x_2^{L,d}(q)}{\partial \bar{c}_1} x_1^{L,d}(q) > \frac{\partial x_2^{H,d}(q)}{\partial \bar{c}_1} x_1^{H,d}(q)$.

Proof. If entry does not occur, the high-cost incumbent's profits are $M_1^H(q) + \delta \overline{M}_1^H(q)$, for a given first-period output q, and for given monopoly profit-maximizing output in the second period of the game. If the incumbent marginally increases first-period output, q, it experiences an increase in profits of

$$\frac{\partial p(q)}{\partial q} q + p(q) + \delta \left[\frac{d\overline{M}_1^K(q)}{dq} \right] - c_1^K \equiv MB^{K,m}(q) - c_1^K.$$

Hence, under no entry, the single-crossing property holds if the incumbent's marginal profits from raising q are larger for the low-cost than for the high-cost incumbent, i.e., $MB^{L,m}(q) - c_1^L \geq MB^{H,m}(q) - c_1^H$. Alternatively, $MR(q) + \delta \left[-\frac{\partial \overline{c_1}^L(q)}{\partial q} x_1^{L,m}(q) \right] - c_1^L \geq MR(q) + \delta \left[-\frac{\partial \overline{c_1}^H(q)}{\partial q} x_1^{H,m}(q) \right] - c_1^H$, where $MR(q) \equiv \frac{\partial p(q)}{\partial q} q + p(q)$, or

$$\delta \left[\frac{\partial \overline{c_1}^L(q)}{\partial q} x_1^{L,m}(q) - \frac{\partial \overline{c_1}^H(q)}{\partial q} x_1^{H,m}(q) \right] < c_1^H - c_1^L \tag{A.3}$$

and since $\frac{\partial \overline{c_1}^L(q)}{\partial q} = \frac{\partial \overline{c_1}^H(q)}{\partial q}$, the above inequality reduces to $\delta \frac{\partial \overline{c_1}^L(q)}{\partial q} \left[x_1^{L,m}(q) - x_1^{H,m}(q) \right] < c_1^H - c_1^L$, which holds by definition given that $\frac{\partial \overline{c_1}^L(q)}{\partial q} < 0$, $x_1^{L,m}(q) > x_1^{H,m}(q)$, and $c_1^H > c_1^L$. [Note that in the case of no learning-by-doing, $\frac{\partial \overline{c_1}^K(q)}{\partial q} = 0$, this condition reduces to $c_1^H > c_1^L$, which is satisfied by definition.]

If entry occurs, the single-crossing property holds if the incumbent's marginal profit from raising q is larger for the low-cost than for the high-cost incumbent, i.e., $MB^{L,d}(q) - c_1^L \geq MB^{H,d}(q) - c_1^H$, where

$$MB^{K,d}(q) \equiv \frac{\partial p(q)}{\partial q} q + p(q) + \delta \left[\frac{dD_1^K(q)}{dq} \right]$$

Rearranging and using the assumption that $\frac{\partial \overline{c_1}^L(q)}{\partial q} = \frac{\partial \overline{c_1}^H(q)}{\partial q}$, we obtain

$$\delta \frac{\partial \overline{c_1}^L(q)}{\partial q} \left[\left(1 - \frac{\partial p(x_1^d, x_2^d)}{\partial x_2^d} \frac{\partial x_2^{L,d}}{\partial \bar{c}_1} \right) x_1^{L,d}(q) - \left(1 - \frac{\partial p(x_1^d, x_2^d)}{\partial x_2^d} \frac{\partial x_2^{H,d}}{\partial \bar{c}_1} \right) x_1^{H,d}(q) \right] < c_1^H - c_1^L$$

or alternatively,

$$\frac{\partial \overline{c_1}^L(q)}{\partial q} \left[x_1^{L,d}(q) - x_1^{H,d}(q) \right] - \left[c_1^H - c_1^L \right] < \frac{\partial \overline{c_1}^L(q)}{\partial q} \frac{\partial p(x_1^d, x_2^d)}{\partial x_2^d} \left[\frac{\partial x_2^{L,d}}{\partial \bar{c}_1} x_1^{L,d}(q) - \frac{\partial x_2^{H,d}}{\partial \bar{c}_1} x_1^{H,d}(q) \right] \tag{A.4}$$

where the left-hand side is negative. The first two terms in the right-hand side are negative. We can hence guarantee that the single-crossing property holds under entry if $\frac{\partial x_2^{L,d}}{\partial \bar{c}_1} x_1^{L,d}(q) > \frac{\partial x_2^{H,d}}{\partial \bar{c}_1} x_1^{H,d}(q)$.

[Note that under no learning-by-doing, $\frac{\partial \overline{c_1}^L(q)}{\partial q} = 0$, condition A.4 reduces to $c_1^H > c_1^L$, which is also satisfied by definition.] ■

6.3 *Proof of Proposition 1*

First, note that entrant's beliefs become $\mu(c_1^H|q^H) = 1$ after observing an equilibrium output of q^H and $\mu(c_1^H|q^L) = 0$ after observing the equilibrium q^L, where $q^L \in \left[q^A, q^B\right]$. If the entrant observes an off-the-equilibrium output $q \neq q^H \neq q^L$, then Bayes' rule does not specify a particular off-the-equilibrium belief, i.e., $\mu(c_1^H|q) \in [0,1]$, and for simplicity we assume $\mu(c_1^H|q) = 1$. Given these beliefs, the entrant enters after observing an output q^H since $D_2^H(q^H) > 0$, but stays out after observing q^L given that $0 > D_2^L(0) > D_2^L(q^L)$. After observing an off-the-equilibrium output $q \neq q^H \neq q^L$, the entrant enters if and only if its expected profit from entering satisfies

$$\mu(c_1^H|q) \times D_2^H(q) + (1 - \mu(c_1^H|q)) \times D_2^L(q) \geq 0, \text{ or}$$

$$\mu(c_1^H|q) \geq \frac{-D_2^L(q)}{D_2^H(q) - D_2^L(q)} \equiv \overline{\mu}(q)$$

where $D_2^H(q) > 0$, implying $D_2^H(q) - D_2^L(q) > -D_2^L(q)$. And since both sides of the inequality are positive, we can conclude that $\overline{\mu}(q)$ satisfies $\overline{\mu}(q) \in [0,1]$.

Let us now examine the high-cost incumbent. By selecting the equilibrium output $q^{H,E}$, the high-cost incumbent obtains profits of $M_1^H(q^{H,E}) + \delta D_1^H(q^{H,E})$. First, note that $q^{H,E}$ maximizes $M_1^H(q) + \delta D_1^H(q)$. Second, first-period output $q^{H,E}$ coincides with the equilibrium output that the high-cost incumbent selects under complete information, yielding the same profits. By deviating towards the low-cost incumbent's equilibrium output, q^L, the high-cost firm obtains profits of $M_1^H(q^L) + \delta \overline{M}_1^H(q^L)$. Hence, the high-cost incumbent prefers to produce an equilibrium output of $q^{H,E}$ rather than deviating towards q^L if $M_1^H(q^{H,E}) + \delta D_1^H(q^{H,E}) \geq M_1^H(q^L) + \delta \overline{M}_1^H(q^L)$, or alternatively,

$$M_1^H(q^{H,E}) - M_1^H(q^L) \geq \delta \left[\overline{M}_1^H(q^L) - D_1^H(q^{H,E})\right] \tag{C1}$$

If instead the high-cost incumbent deviates towards an off-the-equilibrium output of $q \neq q^H \neq q^L$ then entry follows, yielding profits of $M_1^H(q) + \delta D_1^H(q)$, which do not exceed its equilibrium profits of $M_1^H(q^{H,E}) + \delta D_1^H(q^{H,E})$.

Let us now turn to the low-cost incumbent. Selecting the equilibrium first-period output q^L yields $M_1^L(q^L) + \delta \overline{M}_1^L(q^L)$. By deviating towards the high-cost incumbent's equilibrium output, $q^{H,E}$, the low-cost incumbent attracts entry, obtaining profits of $M_1^L(q^{H,E}) + \delta D_1^L(q^{H,E})$. Therefore, the low-cost incumbent selects an equilibrium output of q^L rather than deviating towards $q^{H,E}$ if

$$M_1^L(q^L) + \delta \overline{M}_1^L(q^L) \geq M_1^L(q^{H,E}) + \delta D_1^L(q^{H,E}) \tag{A.5}$$

If instead the low-cost incumbent deviates towards any off-the-equilibrium output of $q \neq q^H \neq$

q^L then entry follows and therefore the incumbent selects the value of q that maximizes profits after entry $M_1^L(q)+\delta D_1^L(q)$. Let $q^{L,E}$ denote the solution to this maximization problem, yielding profits of $M_1^L(q^{L,E})+\delta D_1^L(q^{L,E})$. Hence, the low-cost incumbent chooses an equilibrium output q^L rather than deviating towards $q^{L,E}$ if

$$M_1^L(q^L)+\delta\overline{M}_1^L(q^L)\geq M_1^L(q^{L,E})+\delta D_1^L(q^{L,E}) \tag{A.6}$$

Note that condition A.6 implies A.5 since $M_1^L(q^{L,E})+\delta D_1^L(q^{L,E})>M_1^L(q^{H,E})+\delta D_1^L(q^{H,E})$, given that $q^{L,E}$ maximizes the low-cost incumbent's profits across both periods given entry. Therefore, condition A.6 becomes the condition that must be satisfied in order to guarantee that the low-cost incumbent does not deviate from its equilibrium output of q^L. Let us rewrite this condition as follows

$$M_1^L(q^{L,E})-M_1^L(q^L)\leq\delta\left[\overline{M}_1^L(q^L)-D_1^L(q^{L,E})\right] \tag{C2}$$

Intuitive Criterion. Let us start considering the case in which the low-cost incumbent produces a first-period output of q^B. Let us first check if a deviation towards $q\in(q^A,q^B)$ is equilibrium dominated for either type of incumbent. On one hand, the highest profit that the high-cost incumbent can obtain deviating towards $q\in(q^A,q^B)$ occurs when entry does not follow. In such case, the high-cost incumbent obtains $M_1^H(q)+\delta\overline{M}_1^H(q)$. Hence, it deviates only if $M_1^H(q)+\delta\overline{M}_1^H(q)>M_1^H(q^{H,E})+\delta D_1^H(q^{H,E})$. But condition C1 guarantees that this inequality does not hold for any $q\in(q^A,q^B)$. Hence, the high-cost incumbent does not have incentives to deviate from $q^{H,E}$ to $q\in(q^A,q^B)$.

On the other hand, the highest profit that the low-cost incumbent can obtain from deviating towards $q\in(q^A,q^B)$ occurs when entry does not follow. In such case, the low-cost incumbent's payoff is $M_1^L(q)+\delta\overline{M}_1^L(q)$, which exceeds its equilibrium profits of $M_1^L(q^B)+\delta\overline{M}_1^L(q^B)$ since $M_1^L(q)+\delta\overline{M}_1^L(q)$ reaches its maximum at $q^{L,NE}$ and $q^{L,NE}\leq q^L<q^B$. Therefore, the low-cost incumbent has incentive to deviate from q^B to $q\in(q^A,q^B)$.

Hence, after observing a first-period output of $q\in(q^A,q^B)$, the entrant concentrates its posterior beliefs on the incumbent's costs being low, i.e., $\mu(c_1^H|q)=0$, and does not enter. Given these updated beliefs, the low-cost incumbent obtains $M_1^L(q)+\delta\overline{M}_1^L(q)$ from selecting an output q, which exceeds its equilibrium profit from output q^B. Thus, the low-cost incumbent deviates from q^B, and the separating equilibrium in which it selects q^B violates the Intuitive Criterion. A similar argument is applicable for all separating equilibria in which the low-cost incumbent selects $q\in(q^A,q^B]$, concluding that all of them violate the Intuitive Criterion.

Finally, let us check if the separating equilibrium in which the low-cost incumbent chooses q^A survives the Intuitive Criterion. If the low-cost incumbent deviates towards $q\in(q^A,q^B]$ the highest profit that it can obtain is $M_1^L(q)+\delta\overline{M}_1^L(q)$, which is lower than its equilibrium payoff of $M_1^L(q^A)+\delta\overline{M}_1^L(q^A)$. If instead, it deviates towards $q<q^A$, the highest payoff that it can obtain is $M_1^L(q)+\delta\overline{M}_1^L(q)$, which exceeds its equilibrium profit for all $q\in[q^{L,NE},q^A)$. Hence, the low-cost incumbent has incentives to deviate. Let us now check if the high-cost incumbent also has incentives

to deviate towards $q \in [q^{L,NE}, q^A)$. The highest profit that it can obtain is $M_1^H(q)+\delta\overline{M}_1^H(q)$, which exceeds its equilibrium profit if $M_1^H(q) + \delta\overline{M}_1^H(q) > M_1^H(q^{H,E}) + \delta D_1^H(q^{H,E})$. This condition can be rewritten as

$$\delta\left[\overline{M}_1^H(q) - D_1^H(q^{H,E})\right] > M_1^H(q^{H,E}) - M_1^H(q)$$

which is satisfied for all $q < q^A$ (see figure 1). Hence, the high-cost incumbent also has incentives to deviate towards $q \in [q^{L,NE}, q^A)$.

This implies that, after a deviation in $q \in [q^{L,NE}, q^A)$, the entrant cannot update its prior beliefs, and chooses enter if its expected profit from entering satisfies $p \times D_2^H(q) + (1-p) \times D_2^L(q) > 0$ or

$$p \geq \frac{-D_2^L(q)}{D_2^H(q) - D_2^L(q)} \equiv \overline{p}(q)$$

where $\overline{p}(q) \in (0,1)$ by definition. Hence, if $p \geq \overline{p}(q)$ entry occurs, yielding profits of $M_1^L(q)+\delta D_1^L(q)$ for the low-cost incumbent. Such profits are lower than its equilibrium profits $M_1^L(q^A)+\delta\overline{M}_1^L(q^A)$. Indeed, from C2 we know that $M_1^L(q^A) + \delta\overline{M}_1^L(q^A) \geq M_1^L(q^{L,E}) + \delta D_1^L(q^{L,E})$. Since, in addition, $q^{L,E}$ is the argmax of $M_1^L(q) + \delta D_1^L(q)$, then $M_1^L(q^A) + \delta\overline{M}_1^L(q^A) \geq M_1^L(q) + \delta D_1^L(q)$ for any deviation q. Therefore, the low-cost incumbent does not deviate from q^A. Regarding the high-cost incumbent, it obtains profits of $M_1^H(q) + \delta D_1^H(q)$ by deviating towards q, which are below its equilibrium profits of $M_1^H(q^{H,E}) + \delta D_1^H(q^{H,E})$ since $q^{H,E}$ is the argmax of $M_1^H(q) + \delta D_1^H(q)$. Hence, the high-cost incumbent does not deviate towards q either, and the separating equilibrium survives the Intuitive Criterion for $p > \overline{p}(q)$.

If $p < \overline{p}(q)$, then entry does not occur, yielding profits $M_1^L(q) + \delta\overline{M}_1^L(q)$ for the low-cost incumbent, which exceed its equilibrium profits of $M_1^L(q^A)+\delta\overline{M}_1^L(q^A)$ since $q \in [q^{L,NE}, q^A)$. Then, the separating equilibrium in which the low-cost incumbent selects q^A violates the Intuitive Criterion if $p < \overline{p}(q)$. ■

6.4 *Proof of Proposition 2*

In a pooling strategy profile where both types of incumbent select q, equilibrium beliefs are $\mu\left(c_1^H|q\right) = p$ and $\mu\left(c_1^L|q\right) = 1-p$, which coincide with the prior probability distribution over types. In addition, off-the-equilibrium beliefs cannot be identified using Bayes' rule, and for simplicity let us assume that, after observing $q' \neq q$, $\mu\left(c_1^H|q'\right) = 1$. As shown in the proof of Proposition 1, these beliefs induce the entrant to enter after observing q'. Otherwise the entrant stays out. In particular, after observing q, the entrant enters if and only if $pD_2^H(q) + (1-p)D_2^L(q) \geq 0$ or

$$p \geq \frac{-D_2^L(q)}{D_2^H(q) - D_2^L(q)} \equiv \overline{p}(q)$$

where $D_2^H(q) > 0$, implying that $D_2^H(q) - D_2^L(q) > -D_2^L(q)$, and since both sides of the inequality are positive, we can conclude that the entrant enters if $p > \overline{p}(q)$, and stays out otherwise. Note that if entry occurs after q, this induces every type of incumbent to select $q^{K,E}$. But since $q^{H,E} \neq q^{L,E}$

this strategy profile cannot be a pooling equilibrium. Hence, it must be that $p < \overline{p}(q)$ inducing the entrant to stay out. Let us check under which conditions the high-cost incumbent does not deviate from q. By selecting q, it deters entry obtaining $M_1^H(q) + \delta\overline{M}_1^H(q)$. By deviating towards $q' \neq q$ it attracts entry, yielding a payoff of $M_1^H(q') + \delta D_1^H(q')$, which is maximized at $q^{H,E}$. Hence, the high-cost incumbent does not deviate from q if,

$$M_1^H(q) + \delta\overline{M}_1^H(q) \geq M_1^H(q^{H,E}) + \delta D_1^H(q^{H,E})$$

or equivalently,

$$M_1^H(q^{H,E}) - M_1^H(q) \leq \delta\left[\overline{M}_1^H(q) - D_1^H(q^{H,E})\right] \tag{C1'}$$

and similarly, for the low-cost incumbent,

$$M_1^L(q^{L,E}) - M_1^L(q) \leq \delta\left[\overline{M}_1^L(q) - D_1^L(q^{L,E})\right] \tag{C2}$$

Hence, any q simultaneously satisfying both of the above C1' and C2 conditions for the high and low-cost incumbents constitutes a pooling equilibrium first-period output of the signaling game.

Intuitive Criterion. *Case 1.* Let us now check if the pooling first-period output $q = q^{L,NE}$ survives the Cho and Kreps' (1987) Intuitive Criterion. Let us first check if such output level is equilibrium dominated for either type of incumbent. On one hand, the low-cost incumbent obtains an equilibrium profit of $M_1^L\left(q^{L,NE}\right) + \delta\overline{M}_1^L(q^{L,NE})$. By deviating towards an off-the-equilibrium output level q' such that $q' \neq q^{L,NE}$ the highest payoff that the low-cost incumbent can obtain occurs when entry is deterred, yielding payoffs of $M_1^L(q')+\delta\overline{M}_1^L(q')$, which lies below its equilibrium profits since $M_1^L(q')+\delta\overline{M}_1^L(q')$ reaches its maximum at exactly $q' = q^{L,NE}$. Hence, the low-cost incumbent does not have incentives to deviate from the pooling output $q = q^{L,NE}$. On the other hand, the high-cost incumbent obtains an equilibrium profit of $M_1^H\left(q^{L,NE}\right) + \delta\overline{M}_1^H(q^{L,NE})$. By deviating towards $q' \neq q^{L,NE}$ the highest payoff that the high-cost incumbent can obtain occurs when entry is deterred, yielding payoffs of $M_1^H(q') + \delta\overline{M}_1^H(q')$. Therefore, the high-cost incumbent does not have incentives to deviate if $M_1^H\left(q^{L,NE}\right) + \delta\overline{M}_1^H(q^{L,NE}) \geq M_1^H(q') + \delta\overline{M}_1^H(q')$, which only holds for $q' \in (q^{H,NE}, q^{L,NE})$. Hence, the entrant assigns full probability to the cost being high for every deviation $q' \in (q^{H,NE}, q^{L,NE})$, i.e., $\mu\left(c_1^H|q'\right) = 1$, whereas its updated beliefs are unaffected after observing any other deviation. Thus, after observing $q' \in (q^{H,NE}, q^{L,NE})$, the entrant believes that such deviation can only come from a high-cost incumbent and enters. The high-cost incumbent's profits from deviating towards q' are hence $M_1^H(q')+\delta D_1^H(q')$, which are lower than its equilibrium profits if

$$M_1^H\left(q^{L,NE}\right) + \delta\overline{M}_1^H(q^{L,NE}) \geq M_1^H(q') + \delta D_1^H(q'). \tag{A.7}$$

Note that deviation profits, $M_1^H(q') + \delta D_1^H(q')$, are maximal at $q' = q^{H,E}$, yielding profits of $M_1^H\left(q^{H,E}\right) + \delta D_1^H(q^{H,E})$. Hence, if $M_1^H\left(q^{L,NE}\right) + \delta\overline{M}_1^H(q^{L,NE}) \geq M_1^H\left(q^{H,E}\right) + \delta D_1^H(q^{H,E})$, then condition A.7 holds for all deviations $q' \in (q^{H,NE}, q^{L,NE})$. Rearranging the last inequality,

$$M_1^H\left(q^{H,E}\right) - M_1^H\left(q^{L,NE}\right) \leq \delta\left[\overline{M}_1^H(q^{L,NE}) - D_1^H(q^{H,E})\right]$$

which is satisfied since $q^{L,NE} < q^A$. Therefore, the high-cost incumbent does not have incentives to deviate either, and the pooling PBE in which $q = q^{L,NE}$ survives the Intuitive Criterion.

Case 2. Let us next check if the pooling first-period output $q > q^{L,NE}$ survives the Cho and Kreps' (1987) Intuitive Criterion. On one hand, the low-cost incumbent obtains $M_1^L(q) + \delta\overline{M}_1^L(q)$ in equilibrium. By instead deviating towards $q^{L,NE}$, the highest profit that it can obtain occurs when entry is deterred yielding profits of $M_1^L\left(q^{L,NE}\right) + \delta\overline{M}_1^L(q^{L,NE})$, which exceed its equilibrium profits if $M_1^L\left(q^{L,NE}\right) + \delta\overline{M}_1^L(q^{L,NE}) \geqslant M_1^L(q) + \delta\overline{M}_1^L(q)$, which is true by concavity since $q > q^{L,NE}$. On the other hand, the high-cost incumbent obtains $M_1^H(q) + \delta\overline{M}_1^H(q)$ in equilibrium. By deviating towards $q^{L,NE}$ the highest profit that it can obtain occurs after no entry, yielding profits of $M_1^H\left(q^{L,NE}\right) + \delta\overline{M}_1^H(q^{L,NE})$, which exceed its equilibrium profits since $M_1^H(q) + \delta\overline{M}_1^H(q) \leqslant M_1^H\left(q^{L,NE}\right) + \delta\overline{M}_1^H(q^{L,NE})$, given that $q^{H,NE} < q^{L,NE} < q$ and concavity. Therefore, both types of incumbent have incentives to deviate towards $q^{L,NE}$ and entrant's beliefs cannot be updated, i.e., $\mu\left(c_1^H | q^{L,NE}\right) = p$ inducing no entry. Given these beliefs, both types of incumbent deviate toward $q^{L,NE}$, obtaining higher profits than in equilibrium. Hence, the pooling strategy profile in which both types select $q > q^{L,NE}$ violates the Intuitive Criterion.

Case 3. Let us finally check if the pooling first-period output $q < q^{L,NE}$ survives the Cho and Kreps' (1987) Intuitive Criterion. Let us first consider the case where $q < q^{H,NE} < q^{L,NE}$. On one hand, the low-cost incumbent obtains $M_1^L(q) + \delta\overline{M}_1^L(q)$ in equilibrium. By instead deviating towards $q' \neq q$, the highest profit it can obtain is $M_1^L(q') + \delta\overline{M}_1^L(q')$, which exceeds its equilibrium profit if $q' \in (q, q^{L,NE}]$ given the concavity of the $M_1^L(q') + \delta\overline{M}_1^L(q')$ function with respect to q'. On the other hand, the high-cost incumbent obtains $M_1^H(q) + \delta\overline{M}_1^H(q)$ in equilibrium. By instead deviating towards $q' \neq q$, the highest profit that it can obtain is $M_1^H(q') + \delta\overline{M}_1^H(q')$, which exceeds its equilibrium profit if $q' \in (q, q^{H,NE}]$. Hence, beliefs can be restricted to $\mu\left(c_1^H | q'\right) = 0$ after observing a deviation $q' \in (q^{H,NE}, q^{L,NE}]$. (Otherwise, entrant's beliefs are unaffected, since either both types of incumbent have incentives to deviate or none of them has.) Therefore, after observing a deviation $q' \in (q^{H,NE}, q^{L,NE}]$, the entrant believes that the incumbent's cost must be low, and does not enter. Under these updated beliefs, the low-cost incumbent's profit from deviating exceeds its pooling equilibrium profits. Hence, the low-cost incumbent deviates towards q'. Therefore, the pooling PBE where $q < q^{H,NE} < q^{L,NE}$ violates the Intuitive Criterion.

Let us check if the pooling first-period output q satisfying $q^{H,NE} < q < q^{L,NE}$ survives the Intuitive Criterion. On one hand, the highest payoff that the low-cost incumbent can obtain by deviating towards $q' \neq q$ is $M_1^L(q') + \delta\overline{M}_1^L(q')$, which exceeds its equilibrium profit of $M_1^L(q) + \delta\overline{M}_1^L(q)$ if $q' \in (q, q^{L,NE}]$. On the other hand, the highest payoff that the high-cost firm can obtain by deviating towards $q' \neq q$ is $M_1^H(q') + \delta\overline{M}_1^H(q')$, which exceeds its equilibrium profit of $M_1^H(q) + \delta\overline{M}_1^H(q)$ if $q' \in [q^{H,NE}, q)$. Hence, beliefs can be restricted to $\mu\left(c_1^H | q'\right) = 0$ after observing a deviation $q' \in (q, q^{L,NE}]$, since only the low-cost incumbent has incentives to deviate to this range of output, inducing the entrant to not enter. Under these updated beliefs, the low-cost incumbent's profit from deviating exceeds its pooling equilibrium profits. Hence, the low-cost incumbent deviates towards q' and the pooling PBE where $q^{H,NE} < q < q^{L,NE}$ violates the Intuitive Criterion. ■

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