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By

Ana Espinola-Arredondo and Felix Munoz-Garcia

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

Ana Espínola-Arredondo†
School of Economic Sciences
Washington State University
Pullman, WA 99164

Félix Muñoz-García‡
School of Economic Sciences
Washington State University
Pullman, WA 99164

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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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†Address: 205C Hulbert Hall, Washington State University, Pullman, WA 99164. E-mail: anaespinola@wsu.edu.

‡Address: 103G Hulbert Hall, Washington State University. Pullman, WA 99164-6210. E-mail: fmunoz@wsu.edu. Phone: (509) 335 8402. Fax: (509) 335 1173.

1 Introduction

Several studies analyze monopolists' strategic incentives to deter entrants and maintain their market power. Milgrom and Roberts (1982), for instance, describe an incomplete information entry deterrence model which considers a monopolist incumbent —privately informed about its cost efficiency— and an uninformed entrant. In this context, the inefficient incumbent raises its output level in order to mimic the output decision of the efficient incumbent and thus deter entry, i.e., the incumbent practices "limit pricing." Such increase in first-period output raises consumer welfare, but decreases it in the second period, due to the incumbent's monopolization of the market. When the latter (negative) effect dominates the former (positive) effect, the incumbent's practice of limit pricing produces a decrease in overall consumer welfare, calling for the intervention of antitrust authorities. The regulatory activities of this authority are, however, not a trivial task, given the regulator's lack of accurate information about the firm's profit function.

Our paper investigates entry deterrence in industries where firms benefit from learning-by-doing[1] and analyzes its welfare implications. We show 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 the first period, it increases output in order to mimic the efficient type but also to benefit from learning. In the second period, it enjoys a cost reduction effect due to learning, which ultimately leads the incumbent to raise its output in that period as well. 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 than when they are absent. 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 than when they are not. 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 profits, 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 her ability to identify

[1] Learning-by-doing has been empirically observed in multiple industries. 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) for the production of semiconductor memory chips and Waldman et al. (2003) for health care.

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 shows the role of learning-by-doing as an "ally" of the regulator. Because learning effects can be expected to arise in several technological industries —such as semiconductor memory chips, as documented by Gruber (1992)— and become more significant in the near future, 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), Matthews and Mirman (1983) and Bagwell and Ramey (1988).[2] In addition, it 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,[3] 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. We share relatively similar welfare results with Cabral and Riordan (1997). We provide, however, a benefit from learning-by-doing to antitrust policy that previous papers in the literature did not identify, namely, facilitating the detection of entry deterrence practices.

Section two describes the model and section three develops the case of complete information. In section four we analyze the signaling game under learning-by-doing. We develop a parametric example throughout the paper, similar to that in Fudenberg and Tirole (1983) and Cabral and Riordan (1997), in order to enhance the intuition behind the main results. Section five discusses the implications of our findings in terms of welfare and antitrust policy. In section six, we extend our model to the case in which learning spillovers exist, benefiting not only the incumbent but also the entrant. Finally, section seven concludes.

2 Model

Consider an entry game with an incumbent (Firm 1) operating as a 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 $q_1 > 0$. In the second stage a potential entrant decides whether or not to enter. If entry occurs, agents compete as Cournot

[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] 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).

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.

In the first stage of the game, the incumbent monopoly profits are $M_1^K(q_1) \equiv p(q_1)\, q_1 - c_1^K q_1$, where the inverse demand function, $p(q_1)$, is decreasing and concave in output q_1 and c_1^K indicates the incumbent's marginal costs of production, where $K = \{H, L\}$. In addition, assume that $p(0) \geq c_1^K$, indicating that the marginal willingness to pay for the first unit is higher than the marginal cost associated with its production. During the second period, if entry does not occur, the incumbent produces $x_1 > 0$ obtaining the following monopoly profits

$$\overline{M}_1^K(x_1; q_1) \equiv p(x_1)\, x_1 - \overline{c}_1^K(q_1) x_1,$$

where $p(\cdot)$ is the inverse demand function, which we assume to be constant across periods and $\overline{c}_1^K(q_1)$ denotes the incumbent's marginal costs during the second period. In particular, marginal costs are weakly *decreasing* in first-period output q_1, reflecting the presence of learning-by-doing across periods, i.e., $\frac{\partial \overline{c}_1^K(q_1)}{\partial q_1} \leq 0$. If, instead, $\overline{c}_1^K(q_1)$ is constant in q_1 no learning-by-doing occurs. For simplicity, we consider that learning-by-doing exhibits diminishing returns, i.e., $\overline{c}_1^K(q_1)$ decreases in q_1 but at a decreasing rate, $\frac{\partial^2 \overline{c}_1^K(q_1)}{\partial q_1^2} \geq 0$. Intuitively, a given increase in first-period output causes a larger cost-reduction when the incumbent only produces few units than when its scale becomes large. Let us assume that an increase in first-period output produces the same reduction in second-period costs for the high and low-cost incumbents, i.e., $\frac{\partial \overline{c}_1^H(q_1)}{\partial q_1} = \frac{\partial \overline{c}_1^L(q_1)}{\partial q_1}$. Otherwise, the high-cost incumbent during the first period could become the low-cost incumbent in the following period by producing a sufficiently large first-period output q_1. If entry occurs, firms compete as Cournot duopolists in the second period, with associated profits for the incumbent and entrant respectively,

$$D_1^K(x_1, x_2; q_1) \equiv p(X)\, x_1 - \overline{c}_1^K(q_1) x_1 \quad \text{and} \quad D_2^K(x_2, x_1; q_1) \equiv p(X)\, x_2 - c_2 x_2$$

where $X = x_1 + x_2$ denotes aggregate second-period output, $\overline{c}_1^K(q_1) < c_1^K$ for all $q_1 > 0$, and c_2 represents the entrant's marginal cost. For generality, we do not impose further conditions on c_2, i.e., it can be above or below c_1^K.

3 Complete information

Second period. Let us start examining the second period of the game. In the case of no entry, the incumbent chooses output x_1 that maximizes its second-period monopoly profits

$$\overline{M}_1^K(q_1) \equiv \max_{x_1} \; p(x_1)\, x_1 - \overline{c}_1^K(q_1) x_1 \tag{1}$$

where $x_1^{K,m}(q_1)$ is the profit-maximizing second-period output for a given first-period production q_1.[4] Note that $\overline{M}_1^K(q_1)$ is increasing in first-period output q_1 since, using the envelope theorem, we find that $\frac{d\overline{M}_1^K(q_1)}{dq_1} = -\frac{\partial \overline{c}_1^K(q_1)}{\partial q_1} x_1^{K,m}(q_1)$, which is weakly positive by definition. Intuitively, a marginal increase in first-period output reduces the incumbent's second-period costs, ultimately increasing its profits as a monopolist, $\overline{M}_1^K(q_1)$. Let CRE^m denote the cost-reducing effect under monopoly.

In the case that entry occurs, both firms compete in a duopoly. Hence, for a given equilibrium output of the incumbent under duopoly, $x_1^{K,d}(q_1)$, the entrant selects a profit-maximizing output $x_2^{K,d}(q_1)$ such that

$$D_2^K(q_1) \equiv \max_{x_2} \; p\left(x_1^{K,d}(q_1) + x_2\right) x_2 - c_2 x_2 - E \tag{2}$$

where superscript K indicates the incumbent's type and E denotes the entrant's entry cost. Therefore, the entrant decides to enter if its profits, $D_2^K(q_1)$, are weakly higher than those from staying out, which for simplicity we assume to be zero, i.e., $D_2^K(x_1) \geq 0$. Similarly, the incumbent chooses its profit-maximizing output under duopoly, $x_1^{K,d}(q_1)$, by solving[5]

$$D_1^K(q_1) \equiv \max_{x_1} \; p\left(x_1 + x_2^{K,d}(q_1)\right) x_1 - \overline{c}_1^K(q_1) x_1 \tag{3}$$

Using the envelope theorem on the incumbent's equilibrium second-period duopoly profits,

$$\frac{dD_1^K(q_1)}{dq_1} = \frac{\partial p(x_1, x_2)}{\partial x_2} \frac{\partial x_2^{K,d}}{\partial \overline{c}_1} \frac{\partial \overline{c}_1^K(q_1)}{\partial q_1} x_1^{K,d}(q_1) - \frac{\partial \overline{c}_1^K(q_1)}{\partial q_1} x_1^{K,d}(q_1) \tag{4}$$

The above expression illustrates that a given increase in first-period output produces two positive effects: (1) a *cost-reduction effect* under duopoly (CRE^d), represented by the second term in expression (4) where, for a given entrant's output, the incumbent's costs decrease in q_1; and (2) an *strategic effect* (SE), reflected in the first term, where the entrant reduces its duopoly output $x_2^{K,d}$ when facing a more competitive incumbent.[6] If instead, the incumbent does not benefit from learning-by-doing, then $\frac{\partial \overline{c}_1^K(q_1)}{\partial q_1} = 0$ and both $\overline{M}_1^K(q_1)$ and $D_1^K(q_1)$ are constant in q_1. That is, under no learning-by-doing the incumbent's second-period profits are unaffected by its first-period

[4] Profit-maximizing output $x_1^{K,m}(q_1) > 0$ exists since $p(0) > \overline{c}_1^K(q_1)$ where $x_1 = 0$, and is unique given that $p''(x_1^{K,m})x_1^{K,m} + 2p'(x_1^{K,m}) \leq 0$. Existence and uniqueness is also guaranteed for the case of entry.

[5] It is straightforward to show that $x_1^{K,m}(q_1) > x_1^{K,d}(q_1)$. On one hand, a marginal increase in x_1 produces the same marginal costs under duopoly and monopoly. On the other hand, a marginal increase in x_1 produces a larger marginal revenue under monopoly than under duopoly. In particular, $p(x_1^{K,m})\left[1 + \frac{1}{\varepsilon_{x_1,p}(x_1^{K,m})}\right] > p(x_1^{K,d}, x_2^{K,d})\left[1 + \frac{1}{\varepsilon_{x_1,p}(x_1^{K,d}, x_2^{K,d})}\right]$, where $\varepsilon_{x_1,p}(x_1)$ denotes the price-elasticity of demand. This inequality holds given that the monopolist produces in the elastic region of the demand curve, $\varepsilon_{x_1,p}(x_1^{K,m}) \leq -1$, and $\varepsilon_{x_1,p}(x_1^{K,m}) < \varepsilon_{x_1,p}(x_1^{K,d}, x_2^{K,d})$.

[6] The entrant's profit-maximizing output in (2), $x_2^{K,d}$, is positively related with $\overline{c}_1^K$. Specifically, using the envelope theorem in the maximization problem in (3), it is straightforward to show that the incumbent's second-period output $x_1^{K,d}$ is decreasing in $\overline{c}_1^K$. Since the inverse demand function $p(\cdot)$ is decreasing in output, the entrant's profit-maximizing output from (2), $x_2^{K,d}$, decreases as the incumbent becomes more competitive.

production, both under monopoly and duopoly.[7]

Using the envelope theorem on the entrant's equilibrium duopoly profits,

$$\frac{dD_2^K(q_1)}{dq_1} = \frac{\partial p(x_1, x_2)}{\partial x_1} \frac{\partial x_1^{K,d}}{\partial \overline{c}_1} \frac{\partial \overline{c}_1^K(q_1)}{\partial q_1} x_2^{K,d}(q_1) \tag{5}$$

which is negative by definition.[8] Condition (5) illustrates the negative effect that an increase in first-period output causes on the entrant's duopoly profits, $D_2^K(q_1)$, since the incumbent becomes more competitive in the second period. Note that if, in contrast, learning effects are absent, i.e., $\frac{\partial \overline{c}_1^K(q_1)}{\partial q_1} = 0$, then $D_2^K(q_1)$ becomes constant in q_1. To make the entry decision interesting assume that $0 > D_2^L(q_1)$, reflecting that entry does not occur when the incumbent's initial cost is low, and $D_2^H(q_1) > 0$, illustrating that entry ensues when the cost is high, for all q_1.[9]

First period, No entry. When the incumbent's costs are low, entry does not occur. Hence, the incumbent chooses a first-period output q_1 that solves

$$\max_{q_1} \; p(q_1)q_1 - c_1^L q_1 + \delta \overline{M}_1^L(q_1),$$

where $\delta \in (0,1)$ denotes the incumbent's discount factor. A marginal increase in first-period output produces, on one hand, a marginal cost of c_1^L and, on the other hand, a marginal benefit of $MB^{L,m}(q_1) \equiv \frac{\partial p(q_1)}{\partial q_1} q_1 + p(q_1) + \delta \left[\frac{d\overline{M}_1^L(q_1)}{dq_1} \right]$. The first two terms of this expression coincide with the marginal revenue from an additional unit of output for the standard monopolist without learning-by-doing, $MR(q_1) \equiv \frac{\partial p(q_1)}{\partial q_1} q_1 + p(q_1)$, and the third term represents the additional increase in second-period profits from learning-by-doing. As suggested above, the third term only embodies benefits from the cost-reduction effect under monopoly, CRE^m. In addition, $MB^{L,m}(q_1)$ is decreasing in q_1, 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. Let $q_1^{L,NE}$ denote the solution to the above maximization problem with low costs, where NE represents that no entry occurs.[10]

First period, Entry. When the incumbent's costs are high, entry follows in the second period.

[7] Note that term CRE^d corresponds to what Fudenberg and Tirole (1983) refer as the "marginal incentive in costs," whereas the sum $CRE^d + SE$ corresponds to what they denote as the "marginal incentive in profits."

[8] An increase in the incumbent's second-period marginal costs, $\overline{c_1}$, causes a *decrease* in the incumbent's duopoly output, i.e., $\frac{\partial x_1^{K,d}}{\partial \overline{c_1}} < 0$ in expression (5), but an *increase* in the entrant's duopoly output, i.e., $\frac{\partial x_2^{K,d}}{\partial \overline{c_1}} > 0$, in expression (4).

[9] The incumbent's capacity is hence limited, since it cannot produce a sufficiently large amount during the first period in order to make entry unprofitable.

[10] Existence of $q_1^{L,NE}$ is guaranteed since $p(0) + \delta \left[\frac{d\overline{M}_1^L(0)}{dq_1} \right] > c_1^L$ holds given that $p(0) > c_1^L$ and $\frac{d\overline{M}_1^L(0)}{dq_1} > 0$ by definition. Uniqueness is satisfied since a given increase in q_1 produces $MB_{q_1}^{L,m} \leq \frac{\partial c_1^L}{\partial q_1} = 0$, where $MB_{q_1}^{L,m} = \frac{\partial^2 p(q_1^{L,NE})}{\partial q_1^2} + 2\frac{\partial p(q_1^{L,NE})}{\partial q_1} + \delta \left[\frac{d\overline{M}_1^L(q_1^{L,NE})}{dq_1} \right]$ is negative given that all its terms are negative by definition.

Hence, the incumbent chooses a first-period output q_1 that solves

$$\max_{q_1} \; p(q_1)q_1 - c_1^H q_1 + \delta D_1^H(q_1),$$

In this case a marginal increase in first-period output produces a marginal benefit of $MB^{H,d}(q_1) \equiv \frac{\partial p(q_1)}{\partial q_1} q_1 + p(q_1) + \delta \left[\frac{dD_1^H(q_1)}{dq_1}\right]$. Similarly to our analysis above, the first two terms represent the marginal revenue from an additional unit of output, while the third term indicates the increase in the incumbent's second-period duopoly profits associated to learning-by-doing, embodying both CRE^d and SE. 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, i.e., CRE^m is larger than $CRE^d + SE$. Let $q_1^{H,E}$ denote the solution to the above maximization problem with high costs, where the superscript E represents that entry occurs.[11]

Finally, when no learning-by-doing exists, first-period decisions do not affect second-period profits. That is, both $MB^{L,m}(q_1)$ and $MB^{H,d}(q_1)$ coincide with $MR(q_1)$. In particular, the high-cost incumbent selects a first-period output that maximizes $M_1^H(q_1) + \delta D_1^H$, where duopoly profits during the second stage, D_1^H, are independent on first-period output. Hence, the high-cost incumbent's maximization problem simplifies to a single-period monopoly problem, where the incumbent selects $q_{1,monop}^H$ that maximizes first-period profits $M_1^H(q_1)$. Similarly, the low-cost incumbent chooses q_1 to maximize $M_1^L(q_1) + \delta \overline{M}_1^L$, where second-period monopoly profits, $\overline{M}_1^L$, are independent on first-period output. Thus, the low-cost incumbent selects $q_{1,monop}^L$, where $q_{1,monop}^L > q_{1,monop}^H$.

Note that the difference between the low and high-cost incumbent's equilibrium output when learning effects are present, $q_1^{L,NE} - q_1^{H,E}$, is larger than when learning is absent, $q_{1,monop}^L - q_{1,monop}^H$. Specifically, given no entry and no learning, a marginal increase in first-period output produces the same marginal revenue for the low than for the high-cost incumbent, but different marginal costs, implying $q_{1,monop}^L > q_{1,monop}^H$. Under learning, however, marginal benefits from increasing first-period output differ, i.e., $MB^{L,m} > MB^{H,m}$.[12] Thus, the output difference $q_1^{L,NE} - q_1^{H,NE}$ is positive and larger than $q_{1,monop}^L - q_{1,monop}^H$. Since, in addition, $q_1^{H,NE} > q_1^{H,E}$, we obtain that the output difference $q_1^{L,NE} - q_1^{H,E}$, under learning, is larger than $q_{1,monop}^L - q_{1,monop}^H$, under no learning. The following lemma describes equilibrium output under complete information.

Lemma 1. *The following strategy profile describes the subgame perfect equilibrium of the entry game under complete information:*

1. *In the first period, the high-cost incumbent selects output $q_1^{H,E}$ and the low-cost incumbent chooses $q_1^{L,NE}$. In the second period, the incumbent selects its monopoly output after no*

[11] Existence of $q_1^{H,E}$ is guaranteed since $p(0) + \delta \left[dD_1^H(0)/dq_1\right] > c_1^H$ holds given that $p(0) > c_1^H$ and $dD_1^H(0)/dq_1 > 0$ by definition. Uniqueness holds since a given increase in q_1 produces $MB_{q_1}^{H,d} \leq \frac{\partial c_1^H}{\partial q_1} = 0$.

[12] Note that this is due to volume. Indeed, an increase in q_1 produces the same reduction in both types of incumbent's per-unit cost, $\frac{\partial \overline{c}_1^H(q_1)}{\partial q_1} = \frac{\partial \overline{c}_1^L(q_1)}{\partial q_1}$, but the low-cost incumbent produces a larger second-period output than the high-cost incumbent, thus accruing more CRE benefits.

entry, $x_1^{K,m}(q_1)$, and its duopoly equilibrium output, $x_1^{K,d}(q_1)$, after entry.

2. *The entrant enters when the incumbent's costs are high, selecting the duopoly equilibrium output $x_2^{K,d}(q_1)$, and stays out when the incumbent's costs are low.*

Example. Let us gain further intuition from our results by considering an example with particular functional forms. Assume a linear demand function $p(q_1) = 1 - q_1$ and no discounting, $\delta = 1$. The incumbent's marginal costs are either high c_1^H or low c_1^L, where $1 > c_1^H > c_1^L$, and for simplicity, consider that the entrant's marginal cost, c_2, coincides with that of the high-cost incumbent, i.e., $c_2 = c_1^H$. In the second period, the incumbent's marginal costs, $\overline{c}_1^K(q_1)$, decrease in learning-by-doing as follows $\overline{c}_1^K(q_1) = c_1^K - \lambda q_1$, where $\lambda > 0$ denotes the learning factor and $K = \{H, L\}$. Note that $CRE^m > CRE^d + SE$. When no entry occurs, the incumbent selects output $x_1^{K,m}(q_1) = \frac{1-(c_1^K - \lambda q_1)}{2}$ and $q_1^{K,NE} = \frac{(1-c_1^K)(2+\lambda)}{4-\lambda^2}$ in the second and first period, respectively. Note that both output levels are increasing in the learning factor, λ. In addition, when no learning-by-doing exists, $\lambda = 0$, production in both periods coincides with that under standard single-period monopoly, i.e., $x_1^{K,m} = q_{1,monop}^K = \frac{1-c_1^K}{2}$, where $q_{1,monop}^L > q_{1,monop}^H$. When entry occurs, incumbent and entrant choose $x_1^{K,d}(q_1) = \frac{1+c_2-2(c_1^K - \lambda q_1)}{3}$ and $x_2^{K,d}(q_1) = \frac{1-2c_2+(c_1^K - \lambda q_1)}{3}$ in the second period,[13] while the incumbent selects $q_1^{K,E} = \frac{9+4(1-c_2)\lambda - c_1^K(9+\lambda)}{18-8\lambda^2}$ in the first period.[14] Finally, if $\lambda = 0$, second-period output coincides with that in the single-period duopoly game, becoming $x_1^{K,d} = \frac{1+c_2-2c_1^K}{3}$ and $x_2^{K,d} = \frac{1-2c_2+c_1^K}{3}$, while the incumbent's first-period output becomes $q_{1,monop}^K = \frac{1-c_1^K}{2}$.

4 Signaling the incumbent's costs

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.

2. The incumbent chooses its first-period output level, q_1.

3. Observing the incumbent's output decision, the entrant forms beliefs about the incumbent's initial marginal costs. Let $\mu(c_1^H|q_1)$ denote the entrant's posterior belief about the initial costs being high after observing a particular first-period output from the incumbent q_1.

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

[13] Both firms produce non-negative second-period output if $1 - 2c_2 + c_1^K - \lambda q_1 \geq 0$.

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

5. If entry does not occur, the incumbent maintains its monopoly power, whereas if entry occurs, both agents compete as Cournot duopolists.[15]

In the following lemma we describe under which conditions the single-crossing property holds.

Lemma 2. *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* $\frac{\partial x_2^{L,d}(q_1)}{\partial \overline{c}_1} x_1^{L,d}(q_1) > \frac{\partial x_2^{H,d}(q_1)}{\partial \overline{c}_1} x_1^{H,d}(q_1)$.

Intuitively, when entry does not occur, an increase in q_1 produces, on one hand, a benefit from CRE, which is larger for the low-cost than for the high-cost incumbent. On the other hand, increasing q_1 also imposes an additional production cost, which is lower for the low than for the high-cost incumbent. Thus, a marginal increase in q_1 implies a larger increase in profits for the low than for the high-cost incumbent. When entry occurs, however, an increase in q_1 produces a benefit for the incumbent stemming not only from CRE but also from SE. From our previous discussion we know that the CRE benefit is larger for the low than for the high-cost incumbent. Hence, the incumbent's payoff structure satisfies the single-crossing property if the SE benefit satisfies a similar ranking, i.e., being larger for the low than for the high-cost incumbent, $\frac{\partial x_2^{L,d}(q_1)}{\partial \overline{c}_1} x_1^{L,d}(q_1) > \frac{\partial x_2^{H,d}(q_1)}{\partial \overline{c}_1} x_1^{H,d}(q_1)$.[16] We assume that this property holds throughout the paper.

4.1 Separating equilibrium

Let us next analyze the separating equilibrium where the incumbent selects a first-period output q_1^H when its costs are high, but chooses q_1^L when its costs are low.[17] Entrant's equilibrium beliefs after observing equilibrium output q_1^H and q_1^L are $\mu(c_1^H|q_1^H) = 1$ and $\mu(c_1^H|q_1^L) = 0$, respectively. The entrant enters (stays out) when it infers that the incumbent's initial cost are high (low, respectively). First, we investigate the incentive compatibility 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, i.e., $q_1^{H,E}$, yielding an equilibrium profit of $M_1^H(q_1^{H,E}) + \delta D_1^H(q_1^{H,E})$. If the incumbent deviates towards the low-cost incumbent's output q_1^L, it deters entry. Hence, the high-cost incumbent selects its equilibrium output $q_1^{H,E}$ if $M_1^H(q_1^{H,E}) + \delta D_1^H(q_1^{H,E}) \geq M_1^H(q_1^L) + \delta \overline{M}_1^H(q_1^L)$ or equivalently,[18]

$$M_1^H(q_1^{H,E}) - M_1^H(q_1^L) \geq \delta \left[\overline{M}_1^H(q_1^L) - D_1^H(q_1^{H,E}) \right] \qquad (IC_H)$$

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

[16] This condition holds when the entrant's output $x_2^{K,d}(q_1)$ is linear in the incumbent's costs $\overline{c}_1$. In particular, this implies that $\frac{\partial x_2^{L,d}(q_1)}{\partial \overline{c}_1} = \frac{\partial x_2^{H,d}(q_1)}{\partial \overline{c}_1}$ and hence the single property holds given that $x_1^{L,d}(q_1) > x_1^{H,d}(q_1)$ for all $c_1^L < c_1^H$.

[17] The separating output q_1^L is weakly higher than the production level that the low-cost incumbent selects under complete information, $q_1^{L,NE}$. Otherwise, the high-cost incumbent could be tempted to pool with the low-cost incumbent by selecting $q_1^{L,NE}$.

[18] Incentive compatibility condition IC_H also guarantees that the high-cost incumbent does not have incentives to deviate towards any off-the-equilibrium output q_1 such that $q_1 \neq q_1^{H,E} \neq q_1^L$; see proof of Proposition 1.

Likewise, if the low-cost incumbent chooses the equilibrium output q_1^L, it deters entry, yielding profits of $M_1^L(q_1^L)+\delta\overline{M}_1^L(q_1^L)$. If instead the incumbent deviates towards the high-cost incumbent's output, $q_1^{H,E}$, it attracts entry obtaining a profit of $M_1^L(q_1^{H,E})+\delta D_1^L(q_1^{H,E})$. Conditional on entry, the low-cost incumbent can select an off-the-equilibrium output $q_1 \neq q_1^{H,E} \neq q_1^L$ that achieves a higher profit than that associated to $q_1^{H,E}$. In particular, the incumbent selects an output $q_1^{L,E}$ which maximizes its profits after entry, yielding $M_1^L(q_1^{L,E})+\delta D_1^L(q_1^{L,E})$. Thus, the low-cost incumbent selects its equilibrium output of q_1^L if $M_1^L(q_1^L)+\delta\overline{M}_1^L(q_1^L) \geq M_1^L(q_1^{L,E})+\delta D_1^L(q_1^{L,E})$, or equivalently,

$$M_1^L(q_1^{L,E}) - M_1^L(q_1^L) \leq \delta\left[\overline{M}_1^L(q_1^L) - D_1^L(q_1^{L,E})\right] \qquad (IC_L)$$

The following proposition describes the separating equilibrium of the signaling game.

Proposition 1. *The following strategy profile describes the set of separating Perfect Bayesian Equilibria (PBE) in the signaling game with learning-by-doing:*

1. *In the first period, the high-cost incumbent selects $q_1^{H,E}$ and the low-cost chooses $q_1^L \in [q_1^A, q_1^B]$, where q_1^A and q_1^B solve the incentive compatibility condition for the low and high-cost incumbent, respectively, and $q_1^L > q_1^{L,NE}$;*

2. *The entrant enters only after observing $q_1^{H,E}$, given equilibrium beliefs $\mu(c_1^H|q_1^{H,E})=1$ and $\mu(c_1^H|q_1^L)=0$ for any $q_1^L \in [q_1^A, q_1^B]$, and off-the-equilibrium beliefs $\mu(c_1^H|q_1')=1$ for all $q_1' \neq q_1^{H,E} \neq q_1^L$; and*

3. *In the second period of the game, the incumbent selects an output $x_1^{K,m}(q_1)$ if entry does not occur, and every agent $i=\{1,2\}$ chooses $x_i^{K,d}(q_1)$ if entry occurs.*

The figure below depicts the set of separating equilibria where the high-cost incumbent selects a first-period output $q_1^{H,E}$, which coincides with its output under complete information, and the low-cost incumbent chooses $q_1^L \in [q_1^A, q_1^B]$, which is strictly above its output under complete information, $q_1^{L,NE}$. Specifically, the low-cost incumbent increases its first-period output, relative to complete information, in order to convey its private information to the entrant, deterring it from entering. The curve $\delta\left[\overline{M}_1^K(q_1^L) - D_1^K(q_1^{K,E})\right]$ represents the incumbent's entry deterrence benefits. Specifically, since $\overline{M}_1^K(q_1^L)$ is increasing in q_1^L (due to learning effects) and concave (because diminishing returns in learning-by-doing), then curve $\delta\left[\overline{M}_1^K(q_1^L) - D_1^K(q_1^{K,E})\right]$ is also increasing and concave in q_1^L for $K=\{H,L\}$.[19] In addition, curve $\overline{M}_1^K(q_1^{K,E}) - M_1^K(q_1^L)$ depicts the incumbent's loss in first-period profits of deviating from the first-period output that maximizes profits across both periods given entry, $q_1^{K,E}$. Note that $q_1^{K,E} > q_{1,monop}^K$, and since first-period profits are maximal at $q_{1,monop}^K$, $M_1^K(q_1^{K,E}) < M_1^K(q_{1,monop}^K)$, as represented in the negative region of the figure.

[19] Appendix 1 shows under which conditions $\delta\left[\overline{M}_1^L(q_1^L) - D_1^L(q_1^{L,E})\right]$ is above $\delta\left[\overline{M}_1^H(q_1^L) - D_1^H(q_1^{H,E})\right]$.

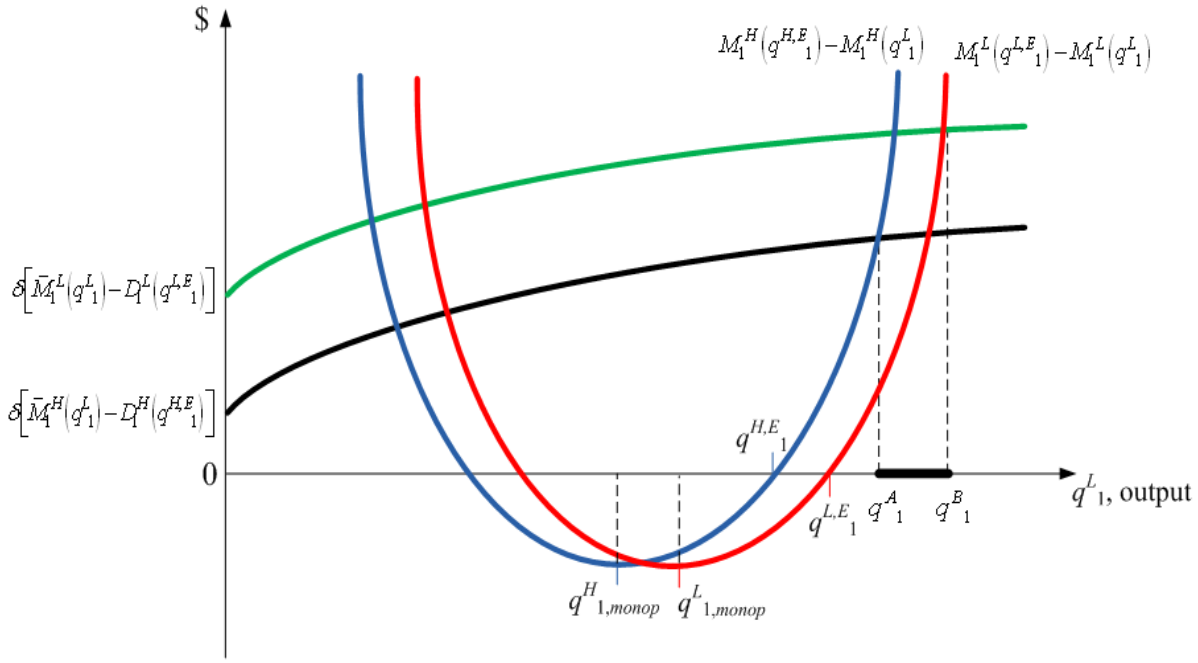

Figure 1. Separating equilibria under learning-by-doing.

If, in contrast, learning-by-doing is absent, the incentive compatibility condition for the high-cost incumbent becomes

$$M_1^H(q^H_{1,monop}) - M_1^H(q^L_1) \geq \delta\left[\overline{M}_1^H - D_1^H\right] \qquad (IC_H)$$

where second-period profits are unaffected by first-period output, both under entry and no entry. Hence, the first-period profit-maximizing output when entry occurs becomes $q^H_{1,monop}$ rather than $q_1^{H,E}$. Similarly, the incentive compatibility condition for the low-cost incumbent is

$$M_1^L(q^L_{1,monop}) - M_1^L(q^L_1) \leq \delta\left[\overline{M}_1^L - D_1^L\right]. \qquad (IC_L)$$

The following figure illustrates the set of separating equilibria under no learning-by-doing. In this context, the high-cost incumbent selects a first-period output $q^H_{1,monop}$, which coincides with its output under complete information and no learning effects. The low-cost incumbent, by contrast, chooses an output in the interval $q_1^L \in [\widetilde{q}_1^A, \widetilde{q}_1^B]$, which is above the first-period output under complete information, $q^L_{1,monop}$. Similarly to the case in which learning is present, the low-cost incumbent increases its first-period output in order to communicate its low cost structure to the potential entrant, deterring entry as a result. Interestingly, our results embody those of Milgrom and Roberts (1982) as a particular case (that arising when learning effects are absent).

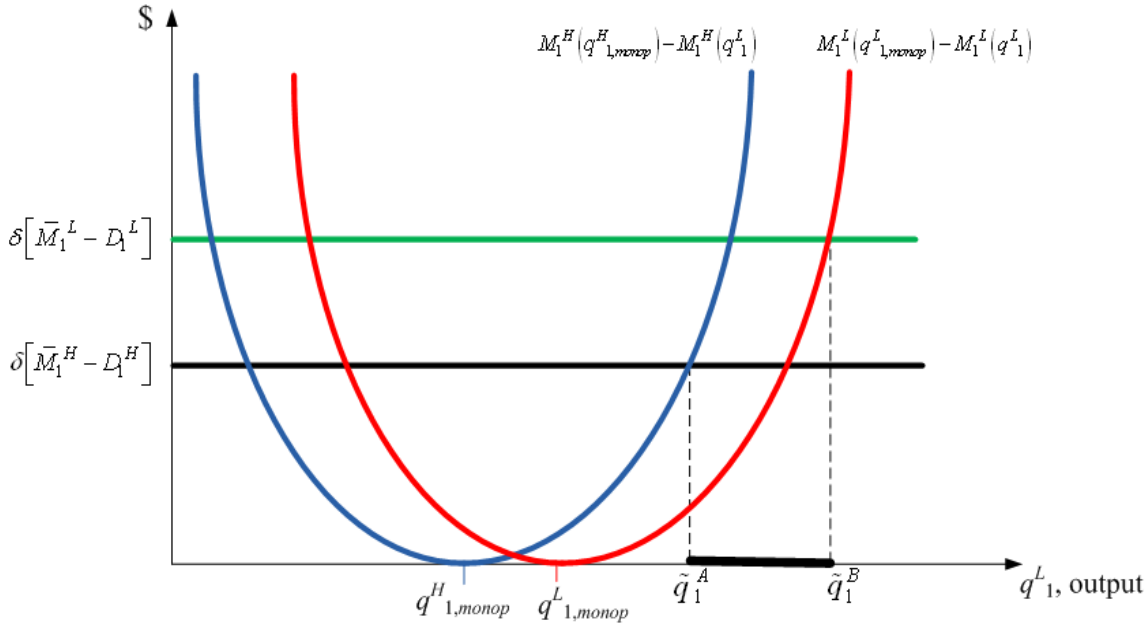

Figure 2. Separating equilibria without learning-by-doing.

A comparison of the above two figures shows that the incumbent's benefit from maintaining its monopoly power is unaffected by its first-period output q_1^L under no learning-by-doing, but becomes increasing when learning-by-doing is present. This benefit —measured by $\overline{M}_1^K - D_1^K$ in figure 2— is indeed constant in q_1^L, but the equivalent benefit under learning-by-doing, $\overline{M}_1^K(q_1^L) - D_1^K(q_1^{K,E})$, becomes increasing in q_1^L (see figure 1). Furthermore, the curve representing the loss in first-period profits from selecting output levels away from $q_{1,monop}^K$ under no learning, $M_1^K(q_{1,monop}^K) - M_1^K(q_1^L)$ in figure 2, lies above the loss in profits from selecting output levels away from $q_1^{K,E}$ under learning (since $q_1^{K,E}$ does not maximizes first-period profits), $M_1^K(q_1^{K,E}) - M_1^K(q_1^L)$. Intuitively, the incumbent is willing to reduce its first-period profits in order to benefit from learning in the second period. Before comparing the set of separating equilibria under different degrees of learning-by-doing, let us apply the Cho and Kreps' (1987) Intuitive Criterion in order to eliminate any "unreasonable" separating equilibria.

Proposition 2. *All separating PBEs identified in Proposition 1 in which the low-cost incumbent selects* $q_1^L \in (q_1^A, q_1^B]$ *violate the Cho and Kreps' (1987) Intuitive Criterion. The least-costly separating equilibrium whereby the low-cost incumbent produces output* q_1^A *survives the Intuitive Criterion if* $p > \overline{p}(q_1)$*, where* $\overline{p}(q_1) \equiv \frac{-D_2^L(q_1)}{D_2^H(q_1) - D_2^L(q_1)}$ *for any off-the-equilibrium output* q_1.

Hence, the low-cost incumbent can signal its type by producing the lowest possible output during the first period. All other production levels (those in the interval $q_1^L \in (q_1^A, q_1^B]$ under learning-by-doing or those in $q_1^L \in (\widetilde{q}_1^A, \widetilde{q}_1^B]$ under no learning-by-doing) would never be selected by the low-cost

incumbent. Indeed, starting from output q_1^B, any lower output also deters entry, and increases the incumbent's monopoly profits. This argument can be repeated for all production levels below q_1^B, inducing the incumbent to reduce its first-period output until q_1^A, which still signals a low cost and thus deters entry. A similar argument holds for the case in which learning-by-doing is not present, whereby the low-cost incumbent selects the lowest output that still induces separation, $\widetilde{q}_1^A$.

Let us next evaluate how much the incumbent increases its first-period output relative to complete information with and without learning-by-doing. We denote the increase in output $\widetilde{q}_1^A - q_{1,monop}^L$ as the "separating effort" when learning effects are absent while $q_1^A - q_1^{L,NE}$ represents that when learning effects are present. The effect of learning on the incumbent's separating effort is ambiguous, since learning produces two opposing effects on the incumbent's separating effort. First, the incumbent's complete information output, $q_1^{L,NE}$, increases in learning, reducing the separating effort for a given q_1^A. Second, the benefits from deterring entry rise in learning, producing an increase in the incumbent's separating effort, for a given $q_1^{L,NE}$. When the second effect dominates the first, a stronger separating result can be sustained under learning effects. This occurs when returns from learning are relatively strong under most output levels. By contrast, a weaker separation result can be supported only when returns from learning exhaust for relatively low levels of output. Note that for standard functional forms, such as those considered in our previous example as well as in Fudenberg and Tirole (1983) and Cabral and Riordan (1997), this does not occur. Instead, the entry deterrence benefit $\overline{M}_1^H(q_1^L) - D_1^H(q_1^{H,E})$ lies above $\overline{M}_1^H - D_1^H$ for any production levels $q_1^L \geqslant q_1^{H,E}$, implying that the incumbent's separating effort is increasing in learning.

Example (cont.) Let us continue with our previous example, applying it to the game under incomplete information. For simplicity, let us assume marginal costs $c_1^H = \frac{1}{2}$ and $c_1^L = \frac{1}{3}$. Under no learning-by-doing, $\lambda = 0$, the low-cost incumbent raises its first-period output from $q_{1,monop}^L = 0.33$ under complete information to $\widetilde{q}_1^A = 0.43$ under the separating equilibrium.[20] Hence, the incumbent slightly deviates from its complete information output in order to convey its private information to the entrant. In contrast, under learning by doing, e.g., $\lambda = \frac{1}{3}$, the low-cost incumbent increases its first-period output from $q_1^{L,NE} = 0.4$ under complete information to $q_1^A = 0.81$ under the separating equilibrium, which implies a larger separating effort than when learning effects are absent. When learning effects are further increased, the incumbent's separating effort $q_1^A - q_1^{L,NE}$ increases to $1.3 - 0.44 = 0.86$ when $\lambda = \frac{1}{2}$, and to $2.84 - 0.50 = 2.34$ when $\lambda = \frac{2}{3}$.

4.2 Pooling equilibrium

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

[20] For compactness, we do not include here the expressions of output levels for any parameter values c_1^H, c_1^L and λ, but they can be provided by the authors upon request.

Proposition 3. *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* $q_1^{L,NE}$*;*
2. *The entrant does not enter after observing the equilibrium output* $q_1^{L,NE}$*, but enters after observing off-the-equilibrium output* q_1'*, given beliefs* $\mu(c_1^H|q_1^{L,NE}) = p < \overline{p}(q_1^{L,NE})$ *and* $\mu(c_1^H|q_1') = 1$*; and*
3. *In the second period of the game, the incumbent selects* $x_1^{K,m}(q_1)$ *if entry does not occur, and every agent* $i = \{1, 2\}$ *chooses* $x_i^{K,d}(q_1)$ *if entry occurs.*

Therefore, in the pooling equilibrium both types of incumbent produce the same first-period output, which reveals no additional information to the entrant, thus deterring entry. Following the same example as in the separating equilibrium $q_1^{L,NE} = \frac{(1-c_1^L)(2+\lambda)}{4-\lambda^2}$ becomes $\frac{1}{3}$ when $\lambda = 0$, $\frac{4}{9}$ when $\lambda = \frac{1}{2}$, and $\frac{8}{15}$ when $\lambda = \frac{2}{3}$.

5 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, an increase in learning effects produces a raise in first and second-period output. This leads to an increase in second-period aggregate output when the entrant's best response function slopes less than unity. In this case, consumer welfare increases in learning during both periods.[21] Otherwise second-period aggregate output decreases, lowering welfare. However, when society assigns a sufficiently low weight to future welfare, the first-period welfare gain offsets the (discounted) second-period welfare loss. This effect arises both in the complete and incomplete information contexts, since equilibrium output coincides in these informational settings for the high-cost incumbent.

When the incumbent's costs are low, first-period output is not only increased to benefit from learning, but also to deter entry, which further increases consumer surplus. Such higher production lowers second-period marginal costs, ultimately increasing monopoly output and consumer surplus in that period as well. In summary, learning produces an increase in social welfare in the complete information setting, and this increase is emphasized in the separating equilibrium. 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.

Let us next evaluate the welfare consequences of an increase in learning in the pooling equilibrium of the game. In the case of low costs, the incumbent produces the same output as under

[21] This condition holds when demand and second-period costs are linear, as in the example developed throughout the paper.

complete information and thus social welfare is unaffected by the informational structure of the game. When costs are high, the incumbent selects a higher level of output, $q_1^{L,NE}$, than in the complete information setting, $q_1^{H,E}$, 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, an increase in learning produces an increase in the first-period welfare gain, since the high-cost incumbent is induced to produce more under learning. On the other hand, learning reduces the second-period welfare loss, because a larger production in the first-period reduces 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. From a regulatory standpoint, the high-cost incumbent's practice of limit pricing in order to deter the entry of potential competitors imposes a *smaller welfare loss* (or a larger welfare gain) when learning effects are present than when they are absent. Our results hence suggest that limit pricing regulation becomes less necessary when learning effects are significant.

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. This arises when learning effects are significant, inducing the predator to substantially increase first-period output (raising welfare in that period), reducing its second-period costs via learning, which ultimately increases second-period output and thus welfare in that period as well. Similarly, in the pooling equilibrium of our model, we show that social welfare can actually increase relative to complete information. Specifically, this arises if the high-cost incumbent's first-period monopoly output is significantly increased, outweighing the negative effects of the second-period monopolization of the market.

Antitrust policy. Note that antitrust authorities analyzing entry do not have incentives to regulate the low-cost incumbent when the separating equilibrium arises, since social welfare in the incomplete information game coincides with that under complete information. When incumbent's costs are high, antitrust authorities do not intervene either if the aforementioned welfare improving conditions hold (i.e., if the entrant's best response function slopes less than unity. Otherwise, if the discount factor is sufficiently low). In the case that both types of incumbent pool selecting the same first-period output level, $q_1^{L,NE}$, we show that regulations becomes less urgent when learning effects are strong. Nonetheless, if the welfare loss associated to the pooling equilibrium is significant, an interesting property of learning is that it makes limit pricing by the high-cost incumbent more "visible" to antitrust authorities. In particular, learning induces the low-cost incumbent to increase its first-period output, from $q_{1,monop}^{L}$ to $q_1^{L,NE}$. In order to pool with the low-cost incumbent, the high-cost incumbent must raise its production under complete information from $q_1^{H,E}$ to $q_1^{L,NE}$, 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 $q_1^{H,E}$ and $q_1^{L,NE}$. If learning effects are small, these 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 $q_1^{H,E}$ and $q_1^{L,NE}$ are further apart, permitting the antitrust authority to identify limit pricing despite having access to relatively inaccurate information about the incumbent's profit function. In summary, learning becomes an "ally" of antitrust authorities seeking to avoid entry deterrence.

6 Extension - Diffusion in learning

In certain contexts the incumbent's cumulative experience not only benefits itself but also the potential entrant.[22] In this case, first-period output still produces a CRE effect, both under monopoly and duopoly. The incumbent's SE 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 selects the same output, $q_1^{L,NE}$, for any diffusion in learning since entry does not follow. In contrast, the high-cost incumbent's first-period output, $q_1^{H,E}$, decreases in the degree of diffusion, given that the incumbent's incentive to reduce its second-period costs decrease in diffusion. The introduction of diffusion, hence, expands the wedge between the low and high-cost incumbent's first-period output under complete information. As a consequence, diffusion reduces the amount of information that the regulator needs to detect the practice of limit pricing.

In the separating equilibrium of the game, the high-cost incumbent selects a first-period output $q_1^{H,E}$ that decreases in diffusion. The effect of diffusion on the low-cost incumbent's separating output is more subtle. Examining figure 1 note that, on one hand, a stronger diffusion produces an upward shift in the curve $M_1^K(q_1^{K,E}) - M_1^K(q_1^L)$ for both types of incumbent. Indeed, the marginal benefit from increasing q_1^L if entry follows decreases in diffusion, since the incumbent obtains a smaller cost advantage relative to the entrant. That is, the incumbent's willingness to give up first-period profits decreases in diffusion. On the other hand, diffusion induces an upward shift in the incumbent's benefit from deterring entry, $\delta[\overline{M}_1^K(q_1^L) - D_1^K(q_1^{K,E})]$. Specifically, $\overline{M}_1^K(q_1^L)$ is unaffected by diffusion —since it only embodies the CRE benefit under monopoly— whereas $D_1^K(q_1^{K,E})$ decreases in diffusion. This occurs because the entrant becomes more competitive as diffusion increases, lowering as a result the incumbent's duopoly profits $D_1^K(q_1^{K,E})$. The incumbent's benefit from deterring entry $\delta[\overline{M}_1^K(q_1^L) - D_1^K(q_1^{K,E})]$ hence increases in diffusion, producing an ambiguous effect on the separating output q_1^A. If an increase in diffusion imposes a larger increase on

[22] 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 (2009). Nonetheless and for completeness we analyze diffusion in learning.

the incumbent's entry deterrence benefit than on the marginal benefit from increasing q_1^L when entry follows, the upward shift in the benefit from deterring entry, $\delta[\overline{M}_1^K(q_1^L) - D_1^K(q_1^{K,E})]$, dominates the upward shift in the curve $M_1^K(q_1^{K,E}) - M_1^K(q_1^L)$, ultimately yielding an increase in the low-cost incumbent output q_1^A. For simplicity, we thereafter consider this condition on the incumbent's profit function.

This result has two implications. First, the low-cost incumbent's separating effort, $q_1^A - q_1^{L,NE}$, increases in diffusion. Intuitively, both types of incumbent have larger entry deterrence benefits, and hence the low-cost incumbent is forced to exert a larger separating effort in order to convey its cost structure to potential entrants and deter entry. Second, an increase in diffusion could result in an increase or decrease in social welfare when the incumbent's costs are high. In particular, diffusion decreases first-period output, $q_1^{H,E}$, as discussed above, raising the incumbent's costs relative to the case of no diffusion. This lowers the incumbent's second-period duopoly output, $x_1^{H,d}$, and increases the entrant's, $x_2^{H,d}$. Hence, aggregate duopoly output depends on the entrant's best-response function. If the entrant responds less than proportionally to a given decrease in the incumbent's second-period output, aggregate duopoly output decreases, and hence social welfare is reduced as well. If instead the entrant responds more than proportionally, second-period output and welfare increases. Therefore, the first-period welfare loss is offset by the (discounted) second-period welfare gain if society assigns a sufficiently high value to future payoffs. If the incumbent's costs are low, diffusion *increases* social welfare. Indeed, this type of incumbent's first-period output increases in diffusion, lowering as a consequence its future costs, which leads to an increase in both first and second-period consumer surplus.

Let us next examine the effect of diffusion on the pooling output level, $q_1^{L,NE}$ which is unaffected by diffusion. In addition, the high-cost incumbent's output under complete information, $q_1^{H,E}$, decreases in diffusion. As a consequence, this incumbent increases its production level when moving from the equilibrium of the complete information game to the pooling equilibrium, and this increase becomes more substantial in diffusion. Intuitively, the high-cost incumbent is willing to give up a larger share of first-period profits in order to avoid a more competitive entrant. Finally, note that diffusion does not affect social welfare when the incumbent's costs are low, since production remains constant, whereas it increases social welfare when they are high, given that output increases in diffusion.

7 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 than when they are absent, 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 still hold or emphasize as diffusion increases.

Note that, for simplicity, we consider that the incumbent does not condition its output decision on the regulator's information, or more generally, on the probability of being audited and fined by antitrust authorities. In an enlarged game, instead, the incumbent could first choose its production level and, observing this output, a regulator decide whether or not to audit (and potentially fine) the incumbent with a positive probability. This new structure of the game would potentially reduce the incumbent's entry deterrence practices, especially when learning-by-doing effects are significant, in the line of our main findings.

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 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.

8 Appendix

8.1 Appendix 1

Let us investigate the conditions under which $\delta\left[\bar{M}_1^L(q_1^L) - D_1^L(q_1^{L,E})\right]$ is above $\delta\left[\bar{M}_1^H(q_1^L) - D_1^H(q_1^{H,E})\right]$. For compactness, let $\overline{M}_1(q_1, c_1)$ denote monopoly second-period equilibrium profits as a function of first-period output, q_1, and the incumbent's initial marginal cost, c_1. Similarly, let $D_1(q_1^E(c_1), c_1)$ 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, $q_1^E(c_1)$. Hence, we next show that the difference $\overline{M}_1(q_1, c_1) - D_1(q_1^E(c_1), c_1)$ is decreasing in the initial cost c_1. In particular, differentiating with respect to c_1 and using the envelope theorem, we obtain

$$-\frac{\partial \overline{c_1}(q_1,c_1)}{\partial c_1} x_1^m(q_1,c_1) - \left[\frac{\partial p\left(x_1^d(q_1,c_1), x_2^d(q_1,c_1)\right)}{\partial x_2^d}\frac{\partial x_2^d(q_1,c_1)}{\partial \overline{c_1}}\frac{\partial \overline{c_1}(q_1,c_1)}{\partial c_1}\right. \tag{A.1}$$

$$\left. - \left(\frac{\partial \overline{c_1}(q_1^E(c_1),c_1)}{\partial q_1}\frac{\partial q_1^E(c_1)}{\partial c_1} + \frac{\partial \overline{c_1}(q_1^E(c_1),c_1)}{\partial c_1}\right)\right] x_1^d(q_1,c_1) \leq 0$$

Note that if learning-by-doing is absent, then $\frac{\partial \overline{c_1}(q_1^E(\theta),\theta)}{\partial q_1^E(\theta)} = 0$ and $\frac{\partial \overline{c_1}(q_1,c_1)}{\partial c_1} = \frac{\partial \overline{c_1}(q_1^E(c_1),c_1)}{\partial c_1} = 1$, and the above condition A.1 is negative if

$$-\left[x_1^m(q_1,c_1) - x_1^d(q_1,c_1)\right] - \left[\frac{\partial p\left(x_1^d(q_1,c_1), x_2^d(q_1,c_1)\right)}{\partial x_2^d}\frac{\partial x_2^d(q_1,c_1)}{\partial \overline{c_1}}\right] x_1^d(q_1,c_1) \leq 0 \tag{A.2}$$

where the first term is negative given that $x_1^m(q_1,c_1) > x_1^d(q_1,c_1)$ for a given q_1 and c_1, and the second term is positive given that $\frac{\partial p\left(x_1^d(q_1,c_1),x_2^d(q_1,c_1)\right)}{\partial x_2^d} < 0$ and $\frac{\partial x_2^d(q_1,c_1)}{\partial \overline{c_1}} > 0$. Hence, condition A.2 holds as long as the inverse demand function is relatively insensitive to increases in output (elastic), i.e., $\frac{\partial p\left(x_1^d(q_1,c_1),x_2^d(q_1,c_1)\right)}{\partial x_2^d}\frac{\partial x_2^d(q_1,c_1)}{\partial \overline{c_1}} \leq \frac{x_1^m(q_1,c_1)}{x_1^d(q_1,c_1)}$. Provided that condition A.2 holds, A.1 is also satisfied if, in addition, $\frac{\partial \overline{c_1}(q_1^E(c_1),c_1)}{\partial q_1}\frac{\partial q_1^E(c_1)}{\partial c_1} > 0$ is relatively small.

Finally, note that the positive slope of $\delta\left[\overline{M}_1^H(q_1^L) - D_1^H(q_1^{H,E})\right]$ is $-\frac{\partial \overline{c_1}^H(q_1)}{\partial q_1} x_1^{H,m}(q_1)$, which is lower than that of $\delta\left[\overline{M}_1^L(q_1^L) - D_1^L(q_1^{L,E})\right]$, $-\frac{\partial \overline{c_1}^L(q_1)}{\partial q_1} x_1^{L,m}(q_1)$, given that $\frac{\partial \overline{c_1}^H(q_1)}{\partial q_1} = \frac{\partial \overline{c_1}^L(q_1)}{\partial q_1}$ by definition and $x_1^{L,m}(q_1) > x_1^{H,m}(q_1)$. Therefore, curve $\delta\left[\overline{M}_1^H(q_1^L) - D_1^H(q_1^{H,E})\right]$ is flatter than $\delta\left[\overline{M}_1^L(q_1^L) - D_1^L(q_1^{L,E})\right]$, guaranteeing that the former does not cross the latter. ■

8.2 *Proof of Lemma 2*

If entry does not occur, the high-cost incumbent's profits are $M_1^H(q_1) + \delta\overline{M}_1^H(q_1)$, for a given first-period output q_1, and for given monopoly profit-maximizing output in the second period of the game. If the incumbent marginally increases first-period output, q_1, it experiences an increase in profits of $MB^{K,m}(q_1) - c_1^K$. Hence, under no entry, the single-crossing property holds if the incumbent's marginal profits from raising q_1 are larger for the low-cost than for the high-cost incumbent,

i.e., $MB^{L,m}(q_1) - c_1^L \geq MB^{H,m}(q_1) - c_1^H$. Alternatively, $MR(q_1) + \delta\left[-\frac{\partial \overline{c_1}^L(q_1)}{\partial q_1} x_1^{L,m}(q_1)\right] - c_1^L \geq MR(q_1) + \delta\left[-\frac{\partial \overline{c_1}^H(q_1)}{\partial q_1} x_1^{H,m}(q_1)\right] - c_1^H$, or

$$\delta\left[\frac{\partial \overline{c_1}^L(q_1)}{\partial q_1} x_1^{L,m}(q_1) - \frac{\partial \overline{c_1}^H(q_1)}{\partial q_1} x_1^{H,m}(q_1)\right] < c_1^H - c_1^L \tag{A.3}$$

and since $\frac{\partial \overline{c_1}^L(q_1)}{\partial q_1} = \frac{\partial \overline{c_1}^H(q_1)}{\partial q_1}$, the above inequality reduces to $\delta\frac{\partial \overline{c_1}^L(q_1)}{\partial q_1}\left[x_1^{L,m}(q_1) - x_1^{H,m}(q_1)\right] < c_1^H - c_1^L$, which holds by definition given that $\frac{\partial \overline{c_1}^L(q_1)}{\partial q_1} < 0$, $x_1^{L,m}(q_1) > x_1^{H,m}(q_1)$, and $c_1^H > c_1^L$. [Note that in the case of no learning-by-doing, $\frac{\partial \overline{c_1}^K(q_1)}{\partial q_1} = 0$, 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_1 is larger for the low-cost than for the high-cost incumbent, i.e., $MB^{L,d}(q_1) - c_1^L \geq MB^{H,d}(q_1) - c_1^H$. Rearranging and using the assumption that $\frac{\partial \overline{c_1}^L(q_1)}{\partial q_1} = \frac{\partial \overline{c_1}^H(q_1)}{\partial q_1}$, we obtain

$$\delta\frac{\partial \overline{c_1}^L(q_1)}{\partial q_1}\left[\left(1 - \frac{\partial p(x_1^d, x_2^d)}{\partial x_2^d}\frac{\partial x_2^{L,d}}{\partial \overline{c}_1}\right) x_1^{L,d}(q_1) - \left(1 - \frac{\partial p(x_1^d, x_2^d)}{\partial x_2^d}\frac{\partial x_2^{H,d}}{\partial \overline{c}_1}\right) x_1^{H,d}(q_1)\right] < c_1^H - c_1^L$$

or alternatively,

$$\frac{\partial \overline{c_1}^L(q_1)}{\partial q_1}\left[x_1^{L,d}(q_1) - x_1^{H,d}(q_1)\right] - \left[c_1^H - c_1^L\right] < \frac{\partial \overline{c_1}^L(q_1)}{\partial q_1}\frac{\partial p(x_1^d, x_2^d)}{\partial x_2^d}\left[\frac{\partial x_2^{L,d}}{\partial \overline{c}_1} x_1^{L,d}(q_1) - \frac{\partial x_2^{H,d}}{\partial \overline{c}_1} x_1^{H,d}(q_1)\right] \tag{A.4}$$

where the left-hand side is negative, as shown in A.3 for the case of entry above. The first two terms in the right-hand side are negative. We can hence guarantee that the single-crossing property holds under entry if $\frac{\partial x_2^{L,d}}{\partial \overline{c}_1} x_1^{L,d}(q_1) > \frac{\partial x_2^{H,d}}{\partial \overline{c}_1} x_1^{H,d}(q_1)$. [Note that under no learning-by-doing, $\frac{\partial \overline{c_1}^L(q_1)}{\partial q_1} = 0$, condition A.4 reduces to $c_1^H > c_1^L$, which is also satisfied by definition.] ■

8.3 *Proof of Proposition 1*

First, note that entrant's beliefs became $\mu(c_1^H|q_1^H) = 1$ after observing an equilibrium output of q_1^H and $\mu(c_1^H|q_1^L) = 0$ after observing the equilibrium q_1^L, where $q_1^L \in \left[q_1^A, q_1^B\right]$. If the entrant observes an off-the-equilibrium output $q_1' \neq q_1^H \neq q_1^L$, then Bayes' rule does not specify a particular off-the-equilibrium belief, i.e., $\mu(c_1^H|q_1') \in [0,1]$, and for simplicity we assume $\mu(c_1^H|q_1') = 1$. Given these beliefs, the entrant enters after observing an output q_1^H since $D_2^H(q_1^H) > 0$, but stays out after observing q_1^L given that $0 > D_2^L(0) > D_2^L(q_1^L)$. After observing an off-the-equilibrium output $q_1' \neq q_1^H \neq q_1^L$, the entrant enters if and only if its expected profit from entering satisfies

$$\mu(c_1^H|q_1') \times D_2^H(q_1') + (1 - \mu(c_1^H|q_1')) \times D_2^L(q_1') > 0$$

$$\mu(c_1^H|q_1') > \frac{-D_2^L(q_1')}{D_2^H(q_1') - D_2^L(q_1')} \equiv \overline{\mu}(q_1')$$

where $D_2^H(q_1') > 0$, implying $D_2^H(q_1') - D_2^L(q_1') > -D_2^L(q_1')$. And since both sides of the inequality are positive, we can conclude that $\overline{\mu}(q_1') \in [0,1]$.

Let us now examine the high-cost incumbent. By selecting the equilibrium output $q_1^{H,E}$, the high-cost incumbent obtains profits of $M_1^H(q_1^{H,E}) + \delta D_1^H(q_1^{H,E})$. First, note that $q_1^{H,E}$ maximizes $M_1^H(q_1) + \delta D_1^H(q_1)$. Second, first-period output $q_1^{H,E}$ 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_1^L, of $M_1^H(q_1^L) + \delta \overline{M}_1^H(q_1^L)$. Hence, the high-cost incumbent prefers to exert an equilibrium output of $q_1^{H,E}$ rather than deviating towards q_1^L if $M_1^H(q_1^{H,E}) + \delta D_1^H(q_1^{H,E}) \geq M_1^H(q_1^L) + \delta \overline{M}_1^H(q_1^L)$, or alternatively,

$$M_1^H(q_1^{H,E}) - M_1^H(q_1^L) \geq \delta \left[\overline{M}_1^H(q_1^L) - D_1^H(q_1^{H,E}) \right] \qquad (IC_H)$$

If instead the high-cost incumbent deviates towards an off-the-equilibrium output of $q_1' \neq q_1^H \neq q_1^L$ then entry follows, yielding profits of $M_1^H(q_1') + \delta D_1^H(q_1')$, which do not exceed its equilibrium profits of $M_1^H(q_1^{H,E}) + \delta D_1^H(q_1^{H,E})$.

Let us now turn to the low-cost incumbent. Selecting the equilibrium first-period output q_1^L yields $M_1^L(q_1^L) + \delta \overline{M}_1^L(q_1^L)$. By deviating towards the high-cost incumbent's equilibrium output, $q_1^{H,E}$, the low-cost incumbent attracts entry, obtaining profits of $M_1^L(q_1^{H,E}) + \delta D_1^L(q_1^{H,E})$. Therefore, the low-cost incumbent selects an equilibrium output of q_1^L rather than deviating towards $q_1^{H,E}$ if

$$M_1^L(q_1^L) + \delta \overline{M}_1^L(q_1^L) \geq M_1^L(q_1^{H,E}) + \delta D_1^L(q_1^{H,E}) \qquad (A.5)$$

If instead the low-cost incumbent deviates towards any off-the-equilibrium output of $q_1' \neq q_1^H \neq q_1^L$ then entry follows and therefore the incumbent selects the value of q_1' that maximizes profits after entry $M_1^L(q_1') + \delta D_1^L(q_1')$. Let $q_1^{L,E}$ denote the solution to this maximization problem, yielding profits of $M_1^L(q_1^{L,E}) + \delta D_1^L(q_1^{L,E})$. Hence, the low-cost incumbent chooses an equilibrium output q_1^L rather than deviating towards $q_1^{L,E}$ if

$$M_1^L(q_1^L) + \delta \overline{M}_1^L(q_1^L) \geq M_1^L(q_1^{L,E}) + \delta D_1^L(q_1^{L,E}) \qquad (A.6)$$

Note that condition A.6 implies A.5 since $M_1^L(q_1^{L,E}) + \delta D_1^L(q_1^{L,E}) > M_1^L(q_1^{H,E}) + \delta D_1^L(q_1^{H,E})$, given that $q_1^{L,E}$ maximizes the low-cost incumbent's profits (across both periods), whereas $q_1^{H,E}$ does not. Therefore, condition A.6 becomes the incentive compatibility condition that must be satisfied in order to guarantee that the low-cost incumbent does not deviate from its equilibrium output of q_1^L. Let us rewrite this incentive compatibility condition as follows

$$M_1^L(q_1^{L,E}) - M_1^L(q_1^L) \leq \delta \left[\overline{M}_1^L(q_1^L) - D_1^L(q_1^{L,E}) \right] \qquad (IC_L)$$

8.4 *Proof of Proposition 2*

Let us start considering the case in which the low-cost incumbent produces a first-period output of q_1^B. Let us first check if a deviation towards $q_1 \in (q_1^A, q_1^B)$ is equilibrium dominated for either type of incumbent. On one hand, the highest profit that the high-cost incumbent can obtain deviating towards $q_1 \in (q_1^A, q_1^B)$ occurs when entry does not follows. In such case, the high-cost incumbent obtains $M_1^H(q_1)+\delta\overline{M}_1^H(q_1)$. Hence, it deviates only if $M_1^H(q_1)+\delta\overline{M}_1^H(q_1) > M_1^H(q_1^{H,E})+\delta D_1^H(q_1^{H,E})$. But IC_H guarantees that this inequality does not hold for any $q_1 \in (q_1^A, q_1^B)$. Hence, the high-cost incumbent does not have incentives to deviate from $q_1^{H,E}$ to $q_1 \in (q_1^A, q_1^B)$.

On the other hand, the highest profit that the low-cost incumbent can obtain from deviating towards $q_1 \in (q_1^A, q_1^B)$ occurs when entry does not follow. In such case, the low-cost incumbent's payoff is $M_1^L(q_1) + \delta\overline{M}_1^L(q_1)$, which exceeds its equilibrium profits of $M_1^L(q_1^B) + \delta\overline{M}_1^L(q_1^B)$ since and $M_1^L(q_1) + \delta\overline{M}_1^L(q_1)$ reaches its maximum at $q_1^{L,NE}$ and $q_1^{L,NE} \geq q_1^L > q_1^B$. Therefore, the low-cost incumbent has incentive to deviate from q_1^B to $q_1 \in (q_1^A, q_1^B)$.

Hence, after observing a first-period output of $q_1 \in (q_1^A, q_1^B)$, the entrant concentrates its posterior beliefs on the incumbent's costs being low, i.e., $\mu(c_1^H|q_1) = 0$, and does not enter. Given these updated beliefs, the low-cost incumbent obtains $M_1^L(q_1) + \delta\overline{M}_1^L(q_1)$ from selecting an output q_1, which exceeds its equilibrium profit from output q_1^B. Thus, the low-cost incumbent deviates from q_1^B, and the separating equilibrium in which it selects q_1^B violates the Intuitive Criterion. A similar argument is applicable for all separating equilibria in which the low-cost incumbent selects $q_1 \in (q_1^A, q_1^B]$, concluding that all of them violate the Intuitive Criterion.

Finally, let us check if the separating in which the low-cost incumbent chooses q_1^A survives the Intuitive Criterion. If the low-cost incumbent deviates towards $q_1 \in (q_1^A, q_1^B]$ the high profit that it can obtain is $M_1^L(q_1) + \delta\overline{M}_1^L(q_1)$, which is lower than its equilibrium payoff of $M_1^L(q_1^A) + \delta\overline{M}_1^L(q_1^A)$. If instead, it deviates towards $q_1 < q_1^A$, the highest payoff that it can obtain is $M_1^L(q_1) + \delta\overline{M}_1^L(q_1)$, which exceeds its equilibrium profit for all $q_1 \in [q_1^{L,NE}, q_1^A)$. Hence, the low-cost incumbent has incentives to deviate. Let us now check if the high-cost incumbent also has incentives to deviate towards $q_1 \in [q_1^{L,NE}, q_1^A)$. The high profit that it can obtain is $M_1^H(q_1) + \delta\overline{M}_1^H(q_1)$, which exceeds its equilibrium profit if $M_1^H(q_1) + \delta\overline{M}_1^H(q_1) > M_1^L(q_1^{H,E}) + \delta D_1^L(q_1^{H,E})$. This condition can be rewritten as

$$\delta\left[\overline{M}_1^H(q_1) - D_1^L(q_1^{H,E})\right] > M_1^L(q_1^{H,E}) - M_1^H(q_1)$$

which is satisfied for all $q_1 < q_1^A$ (see figure 1). Hence, the high-cost incumbent also has incentives to deviate towards $q_1 \in [q_1^{L,NE}, q_1^A)$.

This implies that, after a deviation in $q_1 \in [q_1^{L,NE}, q_1^A)$, the entrant cannot update its prior beliefs, and chooses enter if its expected profit from entering satisfies $p\times D_2^H(q_1)+(1-p)\times D_2^L(q_1) > 0$ or

$$p > \frac{-D_2^L(q_1)}{D_2^H(q_1) - D_2^L(q_1)} \equiv \overline{p}(q_1)$$

where $\overline{p}(q_1) \in (0,1)$ by definition. Hence, if $p > \overline{p}(q_1)$ entry occurs, yielding profits of $M_1^L(q_1) +$

$\delta D_1^L(q_1)$ for the low-cost incumbent. Such profits are lower than its equilibrium profits $M_1^L(q_1^A) + \delta\overline{M}_1^L(q_1^A)$. Indeed, from IC_L we know that $M_1^L(q_1^A)+\delta\overline{M}_1^L(q_1^A) \geq M_1^L(q_1^{L,E})+\delta D_1^L(q_1^{L,E})$. Since, in addition, $q_1^{L,E}$ is the argmax of $M_1^L(q_1)+\delta D_1^L(q_1)$, then $M_1^L(q_1^A)+\delta\overline{M}_1^L(q_1^A) \geq M_1^L(q_1)+\delta D_1^L(q_1)$ for any deviation q_1. Therefore, the low-cost incumbent does not deviate from q_1^A. Regarding the high-cost incumbent, it obtains profits of $M_1^H(q_1) + \delta D_1^H(q_1)$ by deviating towards q_1, which are below its equilibrium profits of $M_1^H(q_1^{H,E}) + \delta D_1^H(q_1^{H,E})$ since $q_1^{H,E}$ is the argmax of $M_1^H(q_1) + \delta D_1^H(q_1)$. Hence, the high-cost incumbent does not deviate towards q_1 either, and the separating equilibrium survives the Intuitive Criterion for $p > \overline{p}(q_1)$.

If $p < \overline{p}(q_1)$, then entry does not occur, yielding profits $M_1^L(q_1) + \delta\overline{M}_1^L(q_1)$ for the low cost incumbent, which exceed its equilibrium profits $M_1^L(q_1^A) + \delta\overline{M}_1^L(q_1^A)$ since $q_1 \in [q_1^{L,NE}, q_1^A)$. Then, the separating equilibrium in which the low-cost incumbent selects q_1^A violates the Intuitive Criterion if $p < \overline{p}(q_1)$. ■

8.5 *Proof of Proposition 3*

In a pooling strategy profile where both types of incumbent select q_1, equilibrium beliefs are $\mu\left(c_1^H|q_1\right) = p$ and $\mu\left(c_1^L|q_1\right) = 1 - p$, 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 $q_1' \neq q_1$, $\mu\left(c_1^H|q_1'\right) = 1$. As shown in the proof of Proposition 1, this beliefs induce the entrant to enter after observing q_1'. Otherwise the entrant stays out. On the other hand, after observing q_1, the entrant enters if and only if $pD_2^H(q_1) + (1-p)D_2^L(q_1) > 0$ or

$$p > \frac{-D_2^L(q_1)}{D_2^H(q_1) - D_2^L(q_1)} \equiv \overline{p}(q_1)$$

where $D_2^H(q_1) > 0$, implying that $D_2^H(q_1) - D_2^L(q_1) > -D_2^L(q_1)$, and since both sides of the inequality are positive, we can conclude that the entrant enters if $p > \overline{p}(q_1)$, and stays out otherwise. Note that if entry occurs after q_1, this induces every type of incumbent to select $q_1^{K,E}$. But since $q_1^{H,E} \neq q_1^{L,E}$ this strategy profile cannot be a pooling equilibrium. Hence, it must be that $p < \overline{p}(q_1)$ inducing the entrant to stay out. Let us check under which conditions the high-cost incumbent does not deviate from q_1. By selecting q_1, it deters entry obtaining $M_1^H(q_1) + \delta\overline{M}_1^H(q_1)$. By deviating towards $q_1' \neq q_1$ it attracts entry, yielding a payoff of $M_1^H(q_1') + \delta D_1^H(q_1')$, which is maximized at $q_1^{H,E}$. Hence, the high-cost incumbent does not deviate from q_1 if,

$$M_1^H(q_1) + \delta\overline{M}_1^H(q_1) \geq M_1^H(q_1^{H,E}) + \delta D_1^H(q_1^{H,E})$$

or equivalently,

$$M_1^H(q_1^{H,E}) - M_1^H(q_1) \leq \delta\left[\overline{M}_1^H(q_1) - D_1^H(q_1^{H,E})\right]$$

and similarly, for the low-cost incumbent,

$$M_1^L(q_1^{L,E}) - M_1^L(q_1) \leq \delta\left[\overline{M}_1^L(q_1) - D_1^L(q_1^{L,E})\right]$$

Hence, any q_1 simultaneously satisfying both of the above incentive compatibility 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 $q_1 = q_1^{L,NE}$ 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 $M_1^L\left(q_1^{L,NE}\right) + \delta\overline{M}_1^L(q_1^{L,NE})$. By deviating towards $q_1' \neq q_1^{L,NE}$ the highest payoff that the low-cost incumbent can obtain occurs when entry is deterred, yielding payoffs of $M_1^L(q_1') + \delta\overline{M}_1^L(q_1')$, which lies below its equilibrium profits since $M_1^L(q_1') + \delta\overline{M}_1^L(q_1')$ reaches its maximum at exactly $q_1' = q_1^{L,NE}$. Hence, the low-cost incumbent does not have incentives to deviate from the pooling output $q_1 = q_1^{L,NE}$. On the other hand, the high-cost incumbent obtains an equilibrium profit of $M_1^H\left(q_1^{L,NE}\right) + \delta\overline{M}_1^H(q_1^{L,NE})$. By deviating towards $q_1' \neq q_1^{L,NE}$ the highest payoff that the high-cost incumbent can obtain occurs when entry is deterred, yielding payoffs of $M_1^H(q_1') + \delta\overline{M}_1^H(q_1')$. Therefore, the high-cost incumbent does not have incentives to deviate if $M_1^H\left(q_1^{L,NE}\right) + \delta\overline{M}_1^H(q_1^{L,NE}) \geq M_1^H(q_1') + \delta\overline{M}_1^H(q_1')$, which only holds for $q_1' \in (q_1^{H,NE}, q_1^{L,NE}]$. Hence, the entrant assigns full probability to the cost being high for every deviation $q_1' \in (q_1^{H,NE}, q_1^{L,NE}]$, i.e., $\mu\left(c_1^H|q_1'\right) = 1$, whereas its updated beliefs are unaffected after observing any other deviation. Thus, after observing $q_1' \in (q_1^{H,NE}, q_1^{L,NE}]$, 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_1' are hence $M_1^H(q_1') + \delta D_1^H(q_1')$, which are lower than its equilibrium profits if

$$M_1^H\left(q_1^{L,NE}\right) + \delta\overline{M}_1^H(q_1^{L,NE}) \geq M_1^H(q_1') + \delta D_1^H(q_1'). \tag{A.7}$$

Note that deviation profits, $M_1^H(q_1') + \delta D_1^H(q_1')$, are maximal at $q_1' = q_1^{H,E}$, yielding profits of $M_1^H\left(q_1^{H,E}\right) + \delta D_1^H(q_1^{H,E})$. Hence, if $M_1^H\left(q_1^{L,NE}\right) + \delta\overline{M}_1^H(q_1^{L,NE}) \geq M_1^H\left(q_1^{H,E}\right) + \delta D_1^H(q_1^{H,E})$, then condition A.7 holds for all deviations $q_1' \in (q_1^{H,NE}, q_1^{L,NE}]$. Rearranging the last inequality,

$$M_1^H\left(q_1^{H,E}\right) - M_1^H\left(q_1^{L,NE}\right) \leq \delta\left[\overline{M}_1^H(q_1^{L,NE}) - D_1^H(q_1^{H,E})\right]$$

which graphically implies that the height of the $M_1^H\left(q_1^{H,E}\right) - M_1^H\left(q_1^L\right)$ curve evaluated at $q_1^L = q_1^{L,NE}$ is lower than the height of the $\delta\left[\overline{M}_1^H(q_1^L) - D_1^H(q_1^{H,E})\right]$ curve also evaluated at $q_1^L = q_1^{L,NE}$. This condition is hence satisfied since $q_1^{L,NE} < q_1^A$. Therefore, the high-cost incumbent does not have incentives to deviate either, and the pooling PBE in which $q_1 = q_1^{L,NE}$ survives the Intuitive Criterion.

Case 2. Let us next check if the pooling first-period output $q_1 > q_1^{L,NE}$ survives the Cho and Kreps' (1987) Intuitive Criterion. On one hand, the low-cost incumbent obtains $M_1^L(q_1) + \delta\overline{M}_1^L(q_1)$ in equilibrium. By instead deviating towards $q_1^{L,NE}$, the highest profit that it can obtain

occurs when entry is deterred yielding profits of $M_1^L\left(q_1^{L,NE}\right)+\delta\overline{M}_1^L(q_1^{L,NE})$, which exceeds its equilibrium profits if $M_1^L\left(q_1^{L,NE}\right)+\delta\overline{M}_1^L(q_1^{L,NE})\geqslant M_1^L(q_1)+\delta\overline{M}_1^L(q_1)$, which is true by concavity since $q_1>q_1^{L,NE}$. On the other hand, the high-cost incumbent obtains $M_1^H(q_1)+\delta\overline{M}_1^H(q_1)$ in equilibrium. By deviating towards $q_1^{L,NE}$ the highest profit that it can obtain occurs after no entry, yielding profits of $M_1^H\left(q_1^{L,NE}\right)+\delta\overline{M}_1^H(q_1^{L,NE})$, which exceed its equilibrium profits since $M_1^H(q_1)+\delta\overline{M}_1^H(q_1)\leqslant M_1^H\left(q_1^{L,NE}\right)+\delta\overline{M}_1^H(q_1^{L,NE})$, given that $q_1^{H,NE}<q_1^{L,NE}<q_1$ and concavity. Therefore, both types of incumbent have incentives to deviate towards $q_1^{L,NE}$ and entrant's beliefs cannot be updated, i.e., $\mu\left(c_1^H|q_1^{L,NE}\right)=p$ inducing no entry. Given these beliefs, both types of incumbent deviate toward $q_1^{L,NE}$, obtaining higher profits than in equilibrium. Hence, the pooling strategy profile in which both types select $q_1>q_1^{L,NE}$ violates the Intuitive Criterion.

Case 3. Let us finally check if the pooling first-period output $q_1<q_1^{L,NE}$ survives the Cho and Kreps' (1987) Intuitive Criterion. On one hand, the low-cost incumbent obtains $M_1^L(q_1)+\delta\overline{M}_1^L(q_1)$ in equilibrium. By instead deviating towards $q_1'\neq q_1$, the highest profit it can obtain is $M_1^L(q_1')+\delta\overline{M}_1^L(q_1')$, which exceeds its equilibrium profit if $q_1'\in(q_1,q_1^{L,NE})$ given the concavity of the $M_1^L(q_1')+\delta\overline{M}_1^L(q_1')$ function with respect to q_1'. On the other hand, the high-cost incumbent obtains $M_1^H(q_1)+\delta\overline{M}_1^H(q_1)$ in equilibrium. By instead deviating towards $q_1'\neq q_1$, the highest profit that it can obtain is $M_1^H(q_1')+\delta\overline{M}_1^H(q_1')$, which exceeds its equilibrium profit if $q_1'\in(q_1,q_1^{H,NE})$. Hence, beliefs can be restricted to $\mu\left(c_1^H|q_1'\right)=0$ after observing a deviation $q_1'\in(q_1^{H,NE},q_1^{L,NE})$. (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 $q_1'\in(q_1^{H,NE},q_1^{L,NE})$, 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 exceed its pooling equilibrium profits. Hence, the low-cost incumbent deviates towards q_1'. Therefore, the pooling PBE where $q_1<q_1^{L,NE}$ violates the Intuitive Criterion. ■

References

[1] Bagwell, K. and G. Ramey (1990) "Advertising and pricing to deter or accommodate entry when demand is unknown," International Journal of Industrial Organization, vol. 8, pp. 93-113.

[2] Baloff, N. (1966) "Startups in machine-intensive production systems." Journal of Industrial Engineering, vol. 31, pp. 679-693.

[3] Cabral, L.M. and M. H. Riordan (1994) "The learning curve, market dominance, and predatory pricing." Econometrica, vol. 62(5), pp. 1115-1140.

[4] Cabral, L. M. B. and M. Riordan (1997) "The learning curve, predation, antitrust and welfare," Journal of Industrial Economics, vol. 2, pp. 157-169.

[5] Dasgupta, P. and J. E. Stiglitz (1988) "Learning-by-doing, market structure, and industrial and trade policies." Oxford Economic Papers, vol. 40(2), pp. 246-268.

[6] Foster, A. D. and M. R. Rosenzweig (1995) "Learning by doing and learning from others: Human capital and technical change in agriculture." Journal of Political Economy, vol. 103(6), pp. 1176-1209.

[7] Fudenberg, D. and J. Tirole (1983) "Learning-by-doing and market performance," Bell Journal of Economics, vol. 14(2), pp. 522-530.

[8] Gruber, H. (1992) "The learning curve in the production of semiconductor memory chips," Applied Economics, vol. 24, pp. 885-894.

[9] Hirsch, W. Z. (1952): "Manufacturing progress functions." Review of Economics and Statistics, vol. 34(2), pp. 143-155.

[10] Hollis, A. (2002) "Strategic implications of learning by doing," International Journal of the Economics of Business, vol. 9(2), pp. 157-174.

[11] Irwin, D. A., and P. J. Klenow (1994) "Learning-by-doing spillovers in the semiconductor industry." Journal of Political Economy, vol. 102(6), pp. 1200-1227.

[12] Lane, F. C. (1951) *Ships for Victory*. Baltimore, MD: Johns Hopkins University Press.

[13] Lieberman, M. B. (1989) "The learning curve, technology barriers to entry, and competitive survival in the chemical processing industries." Strategic Management Journal, vol. 10(5):431-447.

[14] Matthews, S. and Mirmann, L. (1983) "Equilibrium limit pricing: the effects of private information and stochastic demand," Econometrica, vol. 51, pp. 981-996.

[15] Milgrom, P. and J. Roberts (1982) "Limit Pricing and Entry under Incomplete Information," Econometrica, 50, 443-66.

[16] Petrakis, E., E. Rasmusen, and S. Roy (1997) "The learning curve in a competitive industry." RAND Journal of Economics, vol. 28(2), pp. 248-268.

[17] Spence, M. (1981) "The learning curve and competition," Bell Journal of Economics, vol. 12(1), pp. 49-70.

[18] Thompson, P. (2008) "Learning by doing," in Handbook of Economics of Technical Change, edited by B. H. Hall and N. Rosenberg (forthcoming). Elsevier/North-Holland.

[19] Waldman, J. D., S. A. Yourstone, and H. L. Smith (2003) "Learning curves in health care." Health Care Management Review, vol. 28(1), pp. 41-54.

[20] White, L. J. (1977) "The automobile industry," in W. Adams, The structure of American Industry, 5th edition. New York. McMillan.

[21] Wright, T. P. (1936) "Factors affecting the cost of airplanes." Journal of the Aeronautical Sciences, vol. 3(4), pp. 122-128.