Forgoing invention to deter entry[§]

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Abstract

A monopoly facing potential entry may not want to develop an efficient technology even at zero R&D costs. Such a phenomenon occurs if a new technology is distinct from the existing one so production uncertainty becomes technology-specific. Then the monopoly can reduce the entrant's post-entry profit to the point of deterrence by using the existing technology with which the entrant would enter. We show that the monopoly develops a new technology when the entrant faces a sufficiently high or low entry cost but forgoes invention when the entry cost is intermediate. These results hold both in quantity and price competition.

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1. Introduction

We reconsider a monopoly's incentive to develop a new technology under the threat of entry. Suppose that entry can occur when a potential entrant acquires a monopoly's current technology by backward-engineering it or waiting for the patent on it to expire. In such situations the monopoly will naturally have an incentive to develop a more efficient technology to deter entry or stay ahead of the competition. In the presence of production uncertainty however it is possible that the monopoly purposely forgoes the development of a new technology, even at zero R&D cost, so as to deter entry. Such a decision is socially undesirable because a more efficient technology will not be invented and entry will not occur.

We show that the monopoly may forgo the development of a new technology when a new technology is distinct from the existing one so that production uncertainty becomes technology-specific. In such a case, the decision to develop a new technology hinges on three effects. One is the cost-cutting effect of the new technology. The new technology reduces the incumbent's cost, increasing its profit while decreasing the entrant's profit, should entry occur. This clearly favors development of the new technology. In a stochastic environment considered here, however, there are two additional effects that may tilt the scales for the old technology.

A first effect arises from the correlation of firms' strategies that results when the incumbent uses the same existing technology that the entrant does. To see the full consequence of this, suppose that the entrant enters and draws a lower-than-average cost. If the incumbent uses the new technology, the firms' cost realizations are uncorrelated so the entrant produces output in response to the incumbent's expected cost. If the incumbent stays with the old technology, however, the both firms draw the same cost shock, so the entrant responds to the incumbent's low cost; i.e., it produces less output.[1] Similarly, having drawn a higher-than-average cost, the entrant produces more output when the incumbent keeps the old technology than when the incumbent uses the new technology. The use of the old common technology thus dampens output fluctuations. Since profits are convex in output, dampened output variation decreases the entrant's expected profit. If the lower expected profit deters entry, then the old technology has its advantage.[2] We call this the correlation effect.

A final effect affecting the monopoly's technology choice also results from the convexity of profits in output. If output varies more under the old technology than the new, the incumbent tends to prefer the old technology. We call this the relative output variation effect.

The cost-cutting effect and the correlation effect also affect the entrant's expected profit and hence its entry decision. But the entry decision depends not only on the expected profit but the size of the entry cost the entrant faces. Suppose that the entry cost is so high that entry is never profitable regardless of the technology choice the monopoly makes. Then, clearly the monopoly will favor the new technology, given that the relative output variation effect is weak. Alternatively, if the entry cost is so low that entry is inevitable with either technology it uses, then again the monopoly will develop the new technology. When the entry cost is intermediate, however, it is possible that entry be profitable if the monopoly develops the new technology but unprofitable if the monopoly stays with the old technology. In such a case, the monopoly may purposely forgo development of a new technology even at zero R&D cost in order to deter entry. Our analysis thus demonstrates the non-monotonic relationship between the monopoly's incentive to develop the new technology and the monopoly's market power measured ex ante by

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[1] We are abstracting the cost-cutting effect of the new technology to focus on this effect.

[2] A well-known effect of competition with similar firms is that it reduces output fluctuations and so provides insurance (see, e.g., Rey and Tirole 1986). In the strategic environment here this effect instead harms the firms and so can prevent entry.

the entry cost faced by the potential entrant.

Although the idea of developing a more efficient technology to deter entry is not new in the literature, the situation we analyze is novel. Take, for example, the classical work of Gilbert and Newbery (1982). There, an entrant develops a new technology to enter, so a monopoly has a stronger incentive to invent and patent the new technology to deter entry, even if the new technology is inferior to the one the monopoly currently uses.[3] In contrast, in our analysis an entrant enters with the old inferior technology, and the monopoly can decrease the entrant's expected profit by committing to the same inferior technology instead of developing the new technology. In this respect, our results could be characterized as raising-the-rival's-costs strategy (Salop 1979, Salop and Shefffman 1983, 1987).

Our analysis thus finds two new results. A first is that, while the standard literature is concerned with how entry is deterred by development of a new technology, we show how forgoing development of a new technology can deter entry. A second is the non-monotonic relationship between the incumbent's technology choice and the entry cost faced by the entrant; in the standard analysis a new technology can deter entry if it can reduce the entrant's post-entry profit below the unique breakeven entry cost. Furthermore, although our intuition is in the setting of quantity competition, our main results hold both in quantity and price competition. This is unusual as strategic results are usually sensitive to the type of competition and so speaks to the generality of our results.

Finally, our analysis also highlights the role of uncertainty in entry deterrence in a way that has never been analyzed in the literature. For example, Waldman (1987) has considered the effect of uncertainty on non-cooperative entry deterrence and in particular its effect on the free

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[3] Revisiting the problem, Reinganum (1983) shows that an entrant may have a stronger incentive to innovate when invention is stochastic,

rider problem. As we consider a lone incumbent the free rider issue does not arise here. Harrington (1987) has analyzed the effects of uncertainty on entry deterrence when signaling is possible, while signaling cannot arise in our model. Closest to our work, Maskin (1999) has studied the classic model of capacity choice by an incumbent facing a possible entrant under uncertain demand. In it, firms have the same technology and choose capacity sequentially under common (demand) uncertainty. Maskin (1999) shows that it is more difficult to deter entry at times of high demands because the incumbent cannot expand production beyond its capacity level. To deter entry at high demands, therefore, the incumbent must commit to a larger level of capacity than it does in the absence of uncertainty. Commitment to a larger level of capacity, however, reduces marginal profit. Thus, concludes Maskin (1999), the presence of uncertainty makes entry deterrence costlier, thereby facilitating entry, while we find that uncertainty helps to deter entry. The difference is in the settings. In Maskin (1999) the technology is given, and the incumbent must commit to capacity before the resolution of uncertainty. This ex post inflexibility in output hurts the incumbent. In our model, firms choose output after the uncertainty is resolved so they are helped by output fluctuations. The incumbent further benefits from uncertainty through its technology choice as it can affect the entrant's expected profit.

Lastly, we mention Choi and Yi (2000), who examine vertical foreclosure and the choice of input specifications under cost uncertainty. Although distinct from ours in focus, methodologically their work may be most closely related to ours.[4] In their analysis two upstream firms sell inputs to two downstream firms. Each upstream firm can produce a specialized input for one downstream firm or a generalized input that can be used by the both downstream firms. Choi and Yi (2000) show that vertical integration is anticompetitive because an upstream firm

[4] Foreclosure in Choi and Yi (2000) also has the effect of raising the rival's cost and benefiting the integrated firms.

would produce the generalized inputs in a non-integrated vertical structure but, when integrated, it chooses to produce the specialized input for its downstream firm, thereby foreclosing the rival downstream firm. Although the environments differ, their result hinges, like ours, on the fact that the reduction of cost correlation can create a benefit. Specifically, in Choi and Yi (2000) the upstream firms observe cost realizations and then engage in Bertrand competition when producing the generalized inputs. As a result, an upstream firm captures all the profit if it has the lower cost realization but earns zero profits if the rival firm draws the same or lower cost realization. Producing specialized inputs decreases the probability of both firms having the same cost realization and raises expected profits.[5] Thus the firms benefit from a reduction in correlation.

The remainder of the paper is organized in four sections. In section 2 we give a more detailed description of the model. In section 3, we consider the standard model of quantity competition – Cournot competition – in a model in which the incumbent first chooses its technology and then the entrant chooses whether to enter with the old technology. In section 4, we consider price competition in the classic Hotelling model, finding that our result does not qualitatively change. Section 5 concludes.

2. Basic environment

Consider an incumbent monopolist (firm *i*) under the threat of entry (by firm *e*). The incumbent currently holds the patent on the old technology (*O*). When the patent expires the potential entrant can use the old technology and enter the market.[6] The incumbent can continue to use the old technology or develop a new technology (*N*). To focus on the relevant issue we

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[5] As Choi and Yi (2000) note this is also reminiscent of Dasgupta and Maskin's (1987) result that project portfolios are characterized by excessive correlation.

[6] Alternatively, the entrant may enter when it finishes backward-engineering of the incumbent's current technology.

assume the development cost for the new technology is zero.

Firms adopting either technology are subject to technology-specific cost shocks, which can occur, e.g., when the new technology results in a drastically different production process from the one under the old technology. For simplicity, assume that marginal costs are stochastic but constant with respect to output. Let $\bar{c}_O$ denote the expected costs under the old technology and σ_O^2 its variance. Analogously, let $\bar{c}_N$ be the expected costs under the new technology and σ_N^2 its variance. We assume that the new technology is superior in the sense that the expected marginal cost of production is lower: $\bar{c}_N < \bar{c}_O$. We will however make no special assumption about the distributions of c_O and c_N except that their supports are such that firms always produce positive output in equilibrium.[7] This assumption simplifies the analysis considerably without changing the basic insight of the model.

We model the interaction between the firms in four stages. In the first stage, the incumbent chooses (and commits to) its technology. In the second stage, the entrant observes the incumbent's technology choice and chooses whether to enter or not; entry requires fixed entry cost, K. In the third stage, nature draws values for the firms' costs and the firms only observe their own costs. However, if they have the same technology, then the firms can infer each other's costs from observation of their own. In the fourth stage, if the entrant enters, the firms engage in duopolistic competition; otherwise the incumbent remains a monopoly.

3. Cournot competition

In this section we suppose that firms compete in output. The demand function is assumed

[7] The new technology may be sufficiently efficient such that the entrant does not produce with positive probability (and the incumbent always produces). This reduces the expected profits to the potential entrant. Allowing for this possibility however adds no additional insight. Ruling out this possibility simplifies the analysis; in particular it allows for the focus on pure strategy equilibria.

linear for simplicity, and takes the form of

$$p(Q) = 1 - Q$$

if $Q \leq 1$ and $p(Q) = 0$ otherwise. If there is entry, then the firms produce homogeneous products and compete in quantities with aggregate output $Q = q_i + q_e$, where q_i (q_e) is the incumbent's (entrant's) output. Otherwise, the incumbent is a monopoly and so $Q = q_i$.

3.1. Output competition

We solve the model backward, starting with the fourth stage. Begin with the subgame in which the incumbent chooses the old technology and the entrant enters (by default with the old technology). Nature has drawn the cost c_O from distribution O, which is common for both firms. Since they can infer each other's cost by observing their own, the firms play a game of complete information with identical costs. Firm j (= i, e) chooses q_j to maximize

$$\pi_j = (1 - q_k - q_j - c_O) \cdot q_j, \ j \neq k$$

From the first-order condition for each firm the equilibrium quantity and operational profit (i.e., ignoring fixed costs) for firm $j = i$, e are identical to those from the standard symmetric Cournot model, and are given by

$$q_j^O = (1 - c_O)/3, \text{ and}$$

(1) $$\pi_j^O = (1 - c_O)^2/9; \ j = i, e$$

where the superscript O indicates that the incumbent has chosen the old technology.

Consider next the subgame in which the incumbent chooses the new technology and the entrant enters. Then, nature draws a cost realization c_N from distribution N for the incumbent and c_O from distribution O for the entrant. Given independence between O and N, the firms cannot infer each other's cost realization. Thus, the game is one of incomplete information, and we look for a Bayesian-Nash equilibrium.

Firm *j* maximizes expected profit

$$E[(1 - q_j - q_k - c_j)q_j].$$

The first-order condition can be arranged to yield firm *j*'s best response

$$q_j = [1 - c_j - E(q_k)]/2.$$

Given that each firm's cost enters linearly into their best response functions, firm *j*'s expectation of firm *k*'s output is $E(q_k) = [1 - \bar{c}_k - E(q_j)]/2$. Since in a Bayesian-Nash equilibrium the expectations are correct, these equations can be used to obtain the equilibrium outputs

$$q_i^N = [1 - 2c_N + \bar{c}_O]/3 + [c_N - \bar{c}_N]/6$$

$$q_e^N = [1 - 2c_O + \bar{c}_N]/3 + [c_O - \bar{c}_O]/6$$

where the superscript N denotes the incumbent choosing the new technology. Firm *j*, after setting its output (and so knowing its cost), has fourth-stage operational profits of

(2) $$\pi_j^N = \{[2 - 3c_j + 3c_k - \bar{c}_j - \bar{c}_k]/6\}\, q_j^N = (q_j^N)^2$$

Finally, in the subgame where there is no entry, the incumbent chooses q_i to maximize

$$(1 - q_i - c_i)q_i$$

and so *monopoly* operational profits are $\pi_M^O = (1 - c_O)^2/4$ if it chooses the old technology and $\pi_M^N = (1 - c_N)^2/4$ with new technology, where the *M* subscript indicates the monopoly. It is immediate that without potential entry the incumbent would select the new technology because $\bar{c}_N < \bar{c}_O$.

3.2. Technology choice and expected profit to the entrant

Having described the equilibria of the fourth-stage games, we move back to earlier stages. In stage three Nature moves, revealing the technology-specific cost information to the firms only if they chose that technology. In the second stage, the potential entrant makes its entry decision, given the incumbent's technology choice in the first stage. The decision depends on the entry cost and its expected operational profit determined by the technology choice the incumbent makes in the first stage. In this subsection, we derive the entrant's expected operational profit, while the role of the entry cost is discussed in the next subsection.

So, suppose that the incumbent chooses the old technology in the first stage. Then, the potential entrant faces the expected operational profit obtained by taking expectations of (1);

(3) $$E(\pi_e^O) = E(1 - 2c_i + c_e)^2/9 = E(1 - 2c_O + c_O)^2/9$$

$$= (1 - 2\bar{c}_O + \bar{c}_O)^2/9 + E(c_O{}^2 - \bar{c}_O)^2/9$$

$$= \bar{\pi}_e^O + \sigma_O{}^2/9.$$

where

$$\bar{\pi}_e^O \equiv (1 - \bar{c}_O)^2/9$$

is the mean operating profit (i.e., the operating profit if variance equals zero) when the incumbent chooses the old technology. If the incumbent instead chooses the new technology in the first stage, the entrant's expected operational profit obtains from taking expectations of (2):

(4) $$E(\pi_e^N) = E\{[2 - 3c_O + 3c_N - \bar{c}_O - \bar{c}_N]/6\}\cdot\{[1 - 2c_O + \bar{c}_N]/3 + [c_O - \bar{c}_O]/6\}$$

$$= E\{[1 - 2c_O + \bar{c}_N]/3 + [c_O - \bar{c}_O]/6\}^2$$

$$= \bar{\pi}_e^N + \sigma_O{}^2/4$$

where

$$\bar{\pi}_e^N \equiv (1 - 2\bar{c}_O + \bar{c}_N)^2/9$$

is the mean operation profit when the incumbent chooses the new technology.

We can now examine the effect of the incumbent's technology choice on the entrant's expected profit. Notice that in each case the expected profit comprises the mean profit and the variance term. In the absence of the cost-cutting effect ($\overline{c}_O = \overline{c}_N$) the mean profits are identical ($\pi_e^O = \pi_e^N$). Thus, switching to the new technology clearly reduces the entrant's mean profit. However, it also affects the variance terms. Notice that in both cases the variance terms are proportional to the cost variance under the old technology, but that the coefficient of proportionality is smaller when the incumbent uses the old technology than when the incumbent uses the new technology (1/9 versus 1/4). Thus, a switch to the new technology increases the variance term and hence the entrant's expected profit.

The difference between the variance terms, which we called the correlation effect in the introduction, can now be explained. Suppose that the incumbent chooses the old technology, and entry follows. Since the entrant also uses the old technology, the both firms draw the same cost realization. As a result, the entrant can infer the incumbent's cost form its own cost, and responds to the latter's actual best-response function. By contrast, if the incumbent develops a new technology, the firms draw independent cost realizations. Unable to infer the incumbent's actual cost, the entrant responds to the incumbent's mean best-response function.

Now, suppose that the entrant draws a lower-than-average cost. With the old technology, the incumbent also draws the same lower-than-average cost, so the latter's actual best-response function lies outside its mean best-response function. As a result, the entrant produces less output if the incumbent uses the old technology than if the incumbent uses the new technology. Similarly, suppose that the entrant draws a higher-than-average cost. Then, if the incumbent chooses the old technology, the latter's actual best-response function lies inside its mean best-response function. Hence, the entrant produces more output if the incumbent uses the old technology than if the incumbent uses the new technology. Further, given our assumptions of linear demand and constant marginal cost, the incumbent's mean best-response function is identical under either technology, when we abstract from the cost-cutting effect of the new technology. Thus, use of the old technology by the incumbent reduces the entrant's output variation. However, since Cournot profits are given by output squared, and hence are convex in output, dampened output variation reduces the entrant's expected profit.

We have seen that either technology choice can harm the entrant. To see which technology yields more harm, take the difference between (3) and (4) to obtain

$$E[\pi_e^N] - E[\pi_e^O] = (2 - 3\,\bar{c}_O + \bar{c}_N)(-\,\bar{c}_O + \bar{c}_N)/9 + \sigma_O^2/4 - \sigma_O^2/9$$

Hence,

$$E[\pi_e^N] > E[\pi_e^O] \Leftrightarrow$$

$$(5/4)\sigma_O^2 > (\bar{c}_O - \bar{c}_N)(2 - 3\,\bar{c}_O + \bar{c}_N). \qquad (5)$$

The left-hand side of (5) measures the harm to the entrant from the correlation effect. Since the variance terms are proportional to the cost variance of the old technology, the greater the cost variance, the greater the harm, and hence the more likely the entrant prefers that the new technology be chosen. That is, the more likely condition (5) holds. On the other hand, the right-hand side of (5) measures the cost cutting effect of the new technology on the entrant's profit.[8] The smaller this effect, the smaller the right-hand side, and hence the more likely condition (5) holds. In the limit, $\bar{c}_O \rightarrow \bar{c}_N$ so the right-hand side vanishes, in which case condition (5) always

[8] Given our assumption that both firms produce in all states, we have that $2 - 3\,\bar{c}_O + \bar{c}_N > 0$ so that the right-hand side is non-negative.

holds.

To sum, the greater the correlation effect (the cost variance with the old technology), and the smaller the cost-cutting effect of the new technology, the more likely the entrant prefers that the new technology be developed.

3.3. The entry-deterrence set

The decision to enter depends not only on the expected operational profit but also on the entry cost K. Inequality (5) determines when forgoing the new technology reduces the expected profit to the entrant. Now we will determine when it is sufficient to prevent entry. To that end, we first define two critical entry costs: the breakeven entry cost under the old technology K^O by $E(\pi_e^O) - K = 0$ (i.e., for any greater entry cost the entrant does not enter when the old technology is chosen), and the breakeven entry cost under the new technology K^N by $E(\pi_e^N) - K = 0$.

Now, if condition (5) holds, the entrant's profit is greater with the new technology, so the breakeven entry cost is higher with the new technology ($K^O < K^N$). Hence, the interval (K^O, K^N) is non-empty. Therefore, if $K \in (K^O, K^N)$,

$$E[\pi_e^N] - K > 0 > E[\pi_e^O] - K.$$

If this condition holds, the entrant enters if the incumbent develops the new technology and stays out if the incumbent keeps the old technology. We call (K^O, K^N) the entry-deterrence set.

3.4. Entry cost and the optimal technology choice

We are now ready to turn to the first stage of the game, in which the incumbent chooses the technology. Begin with the cases in which the entry cost K is outside the entry deterrence set (K^O, K^N). If $K > K^N$, the net profit to the entrant is negative even if the incumbent chooses the new technology. Therefore, there will be no entry regardless of its technology choice. This case is known as blockaded entry. On the other hand, if K < K^O holds, the entrant's profit is positive even if the incumbent chooses the old technology. Therefore, there will be entry with either technology. For both these cases (either K > K^N or K < K^O), the incumbent's technology choice has no effect on the potential entrant's entry decision, and hence the incumbent clearly will choose the new technology. We state these results in the next proposition.

Proposition 1: In Cournot competition, suppose that (5) holds so the entry-deterrence set (K^O, K^N) is non-empty.

A. If K < K^O the incumbent chooses the new technology, and entry occurs.

B. If $K > K^N$, the incumbent chooses the new technology, and entry is blockaded.

More interesting is the case in which K takes intermediate values, i.e., K is in the entry deterrence set. Then, the incumbent remains a monopoly if it stays with the old technology, but will face entry if it develops the new technology. To determine which technology is more profitable to the incumbent, we compute its expected monopoly profit and duopoly profit. With the old technology the incumbent earns expected monopoly profit of

$$\mathrm{E}[\pi_M^O] = \bar{\pi}_M^O + \sigma_O^2/4,$$

where

$$\bar{\pi}_M^O \equiv (1 - \bar{c}_O)^2/4$$

is mean profit. With development of the new technology, entry occurs so the incumbent earns expected duopoly profit of

$$\mathrm{E}[\pi_i^N] = \mathrm{E}[q_i^N]^2 = \bar{\pi}_i^N + \sigma_N^2/4$$

where

$$\bar{\pi}_i^N \equiv (1 - 2\,\bar{c}_N + \bar{c}_O)^2/9.$$

Therefore, the old technology is more profitable to the incumbent when

$$E[\pi_M^O] \geq E[\pi_i^N] \Leftrightarrow$$

(6) $$(\sigma_O^2 - \sigma_N^2)/4 \;\geq\; \bar{\pi}_i^N - \bar{\pi}_M^O = -[(1 - \bar{c}_O) - 4(\bar{c}_O - \bar{c}_N)](5 - \bar{c}_O - 4\bar{c}_N)/36.$$

We thus obtain:

Proposition 2: In Cournot competition, suppose that (5) holds, so the entry-deterrence set (K^O, K^N) is non-empty. Then, if $K \in (K^O, K^N)$, and (6) holds, the incumbent chooses the old technology and enter is deterred.

We now take a closer look at condition (6). Its left-hand side captures the difference between the variance terms. Note that the variance terms have identical proportionality with respect to the cost variance under the chosen technology. That is because in each case the expected profit is uncorrelated to the entrant's output choice; in the case of monopoly it is by definition, while in the case of duopoly it is due to the independence of cost realizations under separate technologies. Thus, what matters is the size of cost variance under the old technology relative to the new, which we called the relative cost variance effect in the introduction. On the other hand, the right-hand side of (6) represents the difference in mean profit between the two technologies, which reflects the other two effects noted in the introduction. As we saw, with the cost-cutting effect the new technology is more efficient but invites entry, while with the correlation effect the old technology deters entry. The smaller the cost-cutting effect, the smaller the advantage the new technology has over the old, and hence the more likely condition (6) holds, that is, the incumbent prefers not to develop the new technology.

We now look at the last statement more closely; that is, how small the cost cutting effect should be. Suppose that the cost-cutting effect such that we have

$$\bar{c}_O - \bar{c}_N < (1 - \bar{c}_O)/4$$

or equivalently

$$\bar{c}_N \in \left(\bar{c}_O - \frac{(1-\bar{c}_O)}{4}, \bar{c}_O\right). \tag{7}$$

Then the right-hand side of (6) is negative, so condition (6) holds if $\sigma_O^2 \geq \sigma_N^2$, and may hold even if $\sigma_O^2 < \sigma_N^2$.[9] We thus obtain the following corollary to Proposition 2.

Corollary: Suppose that $K \in (K^O, K^N)$, and the cost-cutting effect is sufficiently small so that condition (7) holds. Then the incumbent chooses the old technology over the new technology and deters entry if $\sigma_O^2 \geq \sigma_N^2$.

Of course, if the cost variance is strictly larger under the old technology (i.e., $\sigma_O^2 > \sigma_N^2$), condition (6) may hold even if condition (7) is not met. That is, even if the cost-cutting effect is large, the relative cost variance effect may still make the old technology more attractive.

It is worthwhile to review our main findings. The first result is that an incumbent might not invest in a more efficient technology – even if the investment is costless – *because* the efficient technology is newer and hence uncorrelated to the potential entrant's technology. The reason is that by staying with the old technology the incumbent increases correlation among strategies in the post entry game, reducing the entrant's expected profits to the point of

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[9] In the limit, when $\bar{c}_O \to \bar{c}_N$, the right-hand side approaches $-5(1 - \bar{c}_O)^2/36$ so condition (6) is written $\sigma_O^2 \geq \sigma_N^2 - 5(1 - \bar{c}_O)^2/9$

deterrence. The second result is that, the incumbent's technology choice is non-monotone in the size of fixed entry costs. If the entry cost is so low that entry cannot be deterred with either technology, or so high that entry can be blockaded regardless of its technology choice, the incumbent develops the new technology. For intermediate costs of entry, however, the incumbent may forgo development of the new technology.

These arguments should apply generally whenever use of a common technology correlates strategies between firms and reduces an expected profit to the entrant. For example, in a price competition, drawing a low cost an entrant increases its output but will be less successful in raising profit when an incumbent also faces the same low cost and expanding output. Thus, our results should hold when firms compete in prices instead of output, as we demonstrate in the next section.

4. Price competition

Often in strategic competition the results hinges critically on the type of strategic competition. In this section we examine whether our findings from quantity competition hold when firms compete in prices. To that end, we consider the Hotelling model.

Let there be a linear city of unit length with the incumbent located at 0 and the potential entrant threatens to enter at location 1. Consumers have identical value for the product, v, and linear transportation costs t, which are normalized to one, though for clarity at times we will retain the notation t. Assume further that the market is "covered," $v > c_i + 3t/2$. Otherwise, the assumptions (specifically, regarding the cost distributions) are as before.

We again start first with the fourth stage. Consider the subgames in which the entrant enters (by default with the old technology). The firms set prices simultaneously. Define the location x of the consumer who is just indifferent between the incumbent and the entrant by:

$$v - p_e - t \cdot x = v - p_i - (1 - t) \cdot x$$

From this we obtain firm *j*'s demand

$$q_j = (1 - p_j + p_k)/2.$$

Operational profits for firm *j* are

$$\pi_j = (p_j - c_j)(1 - p_j + p_k)/2$$

with its first order condition

(8) $$1 - 2p_j + p_k + c_j = 0.$$

The remainder of the analysis closely follows the steps from the previous section and so we only sketch the main points. In the subgame in which the incumbent chooses the old technology and the entrant enters, each firm observes the common marginal cost c_O and so the fourth stage is a game of complete information. Using (8), the equilibrium prices and operational profit for firm $j = i, e$ are

$$p_j^O = 1 + c_O.$$

Substituting this into the profit expression yields

$$\pi_j^O = 1/2.$$

If instead the incumbent chooses the new technology and the entrant enters, firms play a game of incomplete information. The Bayesian-Nash equilibrium prices are

$$p_i^N = (3 + 2c_N + \overline{c}_O)/3 + (\overline{c}_N - c_N)/6$$

$$p_e^N = (3 + 2c_O + \overline{c}_N)/3 + (\overline{c}_O - c_O)/6$$

Firm *j*, after setting its price, has fourth-stage operational profits of

(9) $\pi_j^N = (p_j^N - c_j)(6 - 3c_j + 3c_i + \bar{c}_j - \bar{c}_i)/12.$

Finally, if there is no entry, the incumbent's *monopoly* profits are: $\pi_M^O = (v - c_O)^2/4$ if it chooses the old technology and $\pi_M^N = (v - c_N)^2/4$ with new technology, so long $c_i + 2t > v > c_i + 3t/2$, that is, there is an interior solution. If instead there is a corner solution ($v > c_i + 2t$), the results remain qualitatively the same, with the changes noted instead in footnotes for clarity.[10]

Turning to the second stage, if the incumbent chooses the old technology in the first stage, the potential entrant's expected profits is

(10) $E(\pi_e^O) = 1/2.$

If the incumbent chooses instead the new technology, taking expectations of (9) yields the entrant's expected profit

(11) $E[\pi_e^N] = \bar{\pi}_e^N + \sigma_O^2/8$

where

$$\bar{\pi}_e^N \equiv (3 - \bar{c}_O + \bar{c}_N)^2/18$$

is the mean profit.

Comparing the expected profits in (10) and (11), the variance term is smaller (in fact zero) when the incumbent chooses the old technology. Thus the driving force found in quantity competition occurs here as well: by staying with the old technology the incumbent has their costs correlated, thereby reducing the entrant's profits. To see this intuitively, suppose that the entrant, having drawn a lower-than-average marginal cost, lowers the price. If the incumbent uses the new technology, its cost is independently drawn and hence it would not be reacting to the entrant's lower price. However, if it uses the old technology, the incumbent also faces the lower

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[10] If $v > c_i + 2t$, then monopoly profits are $(v - c_i)$.

cost, and decreases its price. As both firms cut prices, the entrant's output does not expand as much as when firms use separate technologies. We have a similar situation when the entrant draws a higher-than-average marginal cost. The incumbent with the old technology also has a higher cost and raises the price, so the entrant's output does not contract as much. Thus, as before, if the incumbent stays with the old technology dampens output fluctuations and results in a lower profit to the entrant than if it develops the new technology.

Comparing the entrant's expected profits in (10) and (11) leads to the following observation:

$$\mathrm{E}[\pi_e^N] > \mathrm{E}[\pi_e^O] \Rightarrow$$

(12) $$\sigma_O^2 > 4(\bar{c}_O - \bar{c}_N)(6 - \bar{c}_O + \bar{c}_N)/9.$$

As with Cournot competition, this condition is more likely to hold, the greater the variance associated with the old technology and the smaller the cost-cutting effect of the new technology. When (12) holds, we can again define the entry-deterrence set (K^O, K^N), with the new-technology and the old-technology breakeven entry cost defined by $K^N \equiv \mathrm{E}[\pi_e^N]$ and $K^O \equiv \mathrm{E}[\pi_e^O]$. For $K \in (K^O, K^N)$, we have

$$\mathrm{E}[\pi_e^N] - K > 0 > \mathrm{E}[\pi_e^O] - K,$$

so entry can be deterred only if K is in the entry deterrence set.

We next turn to the first stage of the game. Given that K is in the entry deterrence set, with the old technology the incumbent earns the monopoly profit:

$$\mathrm{E}[\pi_M^O] = (v - \bar{c}_O)^2/4 + \sigma_O^2/4.$$

The new technology would result in expected duopoly profit

$$\mathrm{E}[\pi_i^N] = \pi_i^N(\bar{c}_N, \bar{c}_O) + \sigma_N^2/8$$

where

$$\pi_i^N(\bar{c}_N, \bar{c}_O) \equiv (3 - \bar{c}_N + \bar{c}_O)^2/18.$$

Therefore,

$$E[\pi_M^O] \geq E[\pi_i^N] \Rightarrow$$

$$\sigma_O^2/4 - \sigma_N^2/8 \ \geq \pi_i^N(\bar{c}_N, \bar{c}_O) - (v - \bar{c}_O)^2/4.$$

As in Cournot competition, the left-hand side is the effect of the relative variance between the two technologies while the right-side side captures the cost-cutting effect of the new technology. However, unlike with Cournot competition the variance term is greater with the monopoly profit than with duopoly profit, which makes the old technology even more attractive to the incumbent.

To abstract from this *additional* benefit from use of the old technology in Hotelling competition, suppose there is no cost uncertainty ($\sigma_N^2 = \sigma_O^2 = 0$).[11] With zero variance, the monopoly chooses the old technology when it deters entry. That occurs if

(14) $$(v - \bar{c}_O)^2/4 > (3 - \bar{c}_N + \bar{c}_O)^2/18.$$

The right-hand side of (14) is decreasing in $\bar{c}_N$, so (14) holds for any $\bar{c}_N$ if it does at $\bar{c}_N = 0$. Setting $\bar{c}_N = 0$ in (14) and solving for v yields $v > \bar{c}_O + \sqrt{2}(3 + \bar{c}_O)/3$.[12,13] Thus, if v is large enough to satisfy this inequality, a monopoly profit with the old technology exceeds a duopoly profit with the new technology no matter how efficient is the new technology.[14]

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[11] Without this assumption our following results hold under even weaker conditions.

[12] There are two roots for v of course, but the lower root implies that $v - \bar{c}_O < 0$.

[13] Since an interior solution is assumed in this analysis, it must be true that $v < \bar{c}_O + 2$. If $\bar{c}_O$ is too large then the critical v, $\bar{c}_O + \sqrt{2}(3 + \bar{c}_O/3 > \bar{c}_O + 2$ and the corner solution case holds (see footnote 15). This requires then that $\bar{c}_O < 3(\sqrt{2} - 1)$ for the interior solution to hold.

[14] If $v > c_i + 2t$, then again for sufficiently large v, being a monopoly with the old technology is more profitable than being a duopolist. See footnote 15.

Even if $v \leq \overline{c}_O + \sqrt{2}(3 + \overline{c}_O)/3$, inspection reveals that (14) still holds if $\overline{c}_N$ equals or is sufficiently close to $\overline{c}_O$, since $v > \overline{c}_O + 3/2$ for the market to be covered. To find the exact condition on $\overline{c}_N$, we rewrite (14) as:

(15) $$\overline{c}_N > 3 + \overline{c}_O - 3(v - \overline{c}_O)/\sqrt{2}.$$

The right-hand side is decreasing in v, so (15) holds if it does at the lowest value of v: $\overline{c}_O + 3/2$, such that the market is covered. Substituting this value for v in (15), we obtain $\overline{c}_N > \overline{c}_O - (9 \cdot 2^{-3/2} - 3) \approx \overline{c}_O - .182$. If this inequality holds, then (14) holds. Summarizing our analysis we have

Proposition 3: In a Hotelling model with an interior solution, suppose that (12) holds and $\overline{c}_N \in (\overline{c}_O - (9 \cdot 2^{-3/2} - 3), \overline{c}_O)$ or $v > \overline{c}_O + \sqrt{2}(3 + \overline{c}_O)/3$. [15]

A. If the potential entrant's fixed (entry) costs $K \in (K^O, K^N)$, then the incumbent chooses the old technology and entry is deterred.

B. If K < K^O the incumbent chooses the new technology and entry occurs.

C. If $K > K^N$, the incumbent chooses the new technology and entry does not occur.

5. Concluding remarks

We develop a model in which a monopoly chooses not to develop a new technology even if the cost of invention is arbitrarily small. Such underinvestment in invention occurs when the monopoly faces a potential entrant having access to the existing technology and if a new technology is so different from the existing technology such that production uncertainty is

[15] If v is sufficiently large that it is optimal for the monopolist to serve the entire market (i.e., $p = v - t$), i.e., there is a corner solution ($v > \overline{c}_O + 2$), then this monopoly profit then this monopoly profit replaces the value for π_M^O in the analysis. In this case, so long $v > [27 + 6(4\overline{c}_O - \overline{c}_N) + (\overline{c}_O - \overline{c}_N)^2]/18 + \sigma^2/8$, , then the inequality in (14) holds.

technology-specific. Then, if the incumbent stays with the existing technology, the entrant would be exposed to the same cost shocks affecting the incumbent. This correlation of costs results in the correlation of strategies between firms and reduces the expected operating profit to the entrant. The incumbent therefore faces a trade-off. The new technology is more efficient but may yield a greater profit to the entrant if its cost-cutting effect is small. The existing technology is less efficient but less likely to induce entry. When an entrant's entry cost is so low that entry is inevitable or it is so high that entry can be blockaded with either technology, the incumbent clearly develops a new technology. When the entry cost is in the intermediate range, however, the incumbent chooses not to invest in new technology and as a result deters entry. Thus the incumbent's responses to the entrant's entry cost are non-monotonic. These results hold when firms compete in quantities as well as in prices. This is unusual since generally these interactions depend on the type of competition.

As an extension of our model, suppose that the entrant's entry cost K is random and revealed to the incumbent after the incumbent has developed the new technology.[16] Then, if K happens to be in the entry deterrence set and other conditions on cost distributions are met, the incumbent will shelve the new and more efficient technology. Examples of such "sleeping patents" include the celebrated Xerox case (Gilbert and Newbery 1982), AT&T's delay in introducing both the handset and dial system and the automatic phone, GE's delay in the introduction of fluorescent bulbs (Dunford 1987) and IBM's delay in introducing new main frames (Scherer 2007).[17]

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[16] We thank the referee for this suggestion.
[17] For more examples see Takalo and Kanniainen (2000) who cite a US Congressional study (1958) that suggest that between 80 and 90% of all patents may be exercised by suppressing (neither using nor licensing it) and the Economic Council of Canada (1971) finding that ''only 15 per cent of the patents granted in the three years covered by the survey have been worked in this country, while 48 per cent have been worked in other countries.''

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