A Duopoly with Asymmetric R&D Investment Disclosure: One Firm Discloses, the Other Conceals

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Abstract

We study a quantity-setting duopoly in which firms 1 and 2 independently choose cost-reducing R&D investments before simultaneously choosing their output levels. After the R&D investments are made, only firm 1's R&D investment is publicly disclosed. Each firm's R&D outcome – its resulting marginal production cost – is deterministically determined. Consequently, when deciding on its R&D investment, each firm is certain of the marginal production cost it will incur. When choosing its output level, firm 2 knows firm 1's new marginal cost. We consider two distinct cases, case I and case II, which differ in the timing of firm 2's R&D decision. In case I, firm 2 chooses its R&D investment *before* observing firm 1's chosen R&D investment. In case II, firm 2 chooses its R&D investment *after* observing firm 1's chosen R&D investment. Unlike Baik and Lee (2025), who analyze duopolies with asymmetric delegation-contract disclosure, we show that the outcomes in case I differ from those in case II.

Keywords: Asymmetric R&D investment Disclosure; Cost-reducing R&D investment; Deterministic R&D process; Duopoly; Hidden R&D investment

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1. Introduction

Consider a strategic interaction between two parties, each of whom makes two sequential moves. Before choosing their second actions, one party selects and publicly discloses its first action, whereas the rival party chooses its first action without disclosing it. The two parties then choose their second actions simultaneously.[1]

Recently, Baik and Lee (2025) examine such two-party strategic interactions by formulating two general games with imperfect and asymmetric information – referred to as game I and game II – and by developing a solution technique for each. Suppose that party 1 publicly discloses its first action, whereas party 2 does not disclose its own. The two games differ in the timing of the parties' first moves. In game I, party 2 chooses its first action *before* observing the first action chosen by party 1; thus both parties choose their first actions without observing their rival's choice. In game II, by contrast, party 2 chooses its first action *after* observing party 1's chosen first action. In both games, however, each party has the same information structure regarding the first actions chosen by both parties when choosing its second action.

As an application, Baik and Lee (2025) formulate and analyze two games – game I and game II – in a quantity-setting duopoly with managerial delegation.[2] In game I, the owner of each firm first offers a contract to her manager *without* observing the rival owner's choice. Next, owner 1 publicly discloses her chosen contract, whereas owner 2 does not disclose her own. Finally, managers 1 and 2 choose their firms' output levels simultaneously and independently. In game II, by contrast, owner 1 first offers a contract to manager 1 and discloses it publicly. Then, *after* observing firm 1's contract, owner 2 offers a contract to manager 2 but does not disclose it. Finally, managers 1 and 2 choose their firms' output levels simultaneously and independently.

Interestingly, Baik and Lee (2020, 2025) show that the outcomes – the equilibrium contracts, output levels, and profits of the firms – in game I are identical to those in game II.

The purpose of this paper is to formulate and analyze two games – game I and game II – in a quantity-setting duopoly with R&D competition, and to examine whether these games

yield identical outcomes. Game I proceeds as follows. First, each firm chooses its R&D investment *without* observing the rival's choice. Next, firm 1 publicly discloses its R&D investment, whereas firm 2 does not disclose its own. Finally, both firms choose their output levels simultaneously and independently. By contrast, game II proceeds as follows. First, firm 1 chooses and discloses its R&D investment publicly. Next, *after* observing firm 1's R&D investment, firm 2 chooses its R&D investment but does not disclose it. Finally, both firms choose their output levels simultaneously and independently.

In Section 3, we show that the outcomes differ between the two games. Specifically, firm 1's equilibrium R&D investment, output level, and profits are lower in game I than in game II. In contrast, firm 2's equilibrium R&D investment, output level, and profits are higher in game I than in game II.

This paper is also related to studies that examine whether firms endogenously disclose information about their R&D investments. Jiang and Xiong (2025) and Baik and Kim (2025) analyze a quantity-setting duopoly with R&D competition in which each firm can choose whether to disclose its cost-reducing R&D investment. Their games proceed as follows. First, each firm decides and announces whether it will disclose its R&D investment. Next, each firm chooses its R&D investment and discloses it if it has committed to doing so. Finally, the firms choose their output levels simultaneously and independently. Analyzing these games requires consideration of three scenarios: both firms disclose, neither firm discloses, and only one firm discloses its R&D investment. To study the asymmetric case in which only one firm discloses, the authors construct games similar to game I in the current paper.

The remainder of the paper is organized as follows. Section 2 sets up games I and II in a quantity-setting duopoly with R&D competition, where only one firm publicly discloses its R&D investment before both firms simultaneously and independently choose their output levels. Section 3 analyzes the two games and compares their outcomes. Section 4 concludes.

2. Quantity-setting duopoly with asymmetric R&D investment disclosure

Consider a duopoly in which two profit-maximizing firms, 1 and 2, produce homogeneous products. The firms first make R&D investments independently to reduce their production costs. After these investments are made, firm 1 discloses its R&D investment publicly, while firm 2 chooses not to disclose its R&D investment. Finally, both firms produce their products at the reduced costs and compete with each other in terms of quantity in the market.

Let x_i, for $i = 1, 2$, denote firm i's R&D investment, where $x_i > 0$. We assume that the R&D cost function of firm i is $K(x_i) = \gamma x_i^2/2$, where $\gamma \geq 1$.[3] Let c_i denote firm i's constant marginal production cost, and q_i its output level, where $c_i > 0$ and $q_i \geq 0$. We assume that the cost function of firm i is $V_i(q_i) = c_i q_i$ for all $q_i \in R_+$.

We assume that the firms initially have the same marginal production cost, denoted by c^M, prior to making their R&D investments, where $c^M > 0$. This initial marginal production cost is publicly known. After making their R&D investments, the firms' new marginal production costs are *deterministically* determined.[4] This implies that, when making its R&D investment, each firm is certain about its own new marginal production cost that results from its chosen R&D investment. Firm i's new marginal production cost, resulting from its R&D investment x_i, is given by $c^M - \delta x_i$, where $0 < \delta < 0.5$ and $x_i \in (0, c^M/\delta)$.[5]

When the firms choose their output levels, neither can directly observe the other's new marginal production cost. However, because firm 1 disclosed its R&D investment, firm 2 knows firm 1's new marginal production cost. Since firm 2 did not disclose its own R&D investment, firm 1 infers firm 2's new marginal production cost by forming a belief about firm 2's R&D investment.

The market price is determined by

$$P = \begin{cases} a - Q & \text{for } 0 \leq Q \leq a \\ 0 & \text{for } Q > a, \end{cases}$$

where $a > 0$ and $Q = q_1 + q_2$. We assume that $0 < c^M < a$.

We consider two cases, distinguished by the timing of firm 2's R&D decision. In case I, firm 2 chooses its R&D investment *before* observing firm 1's R&D investment. Consequently, in this scenario, each firm chooses its R&D investment *without* observing the R&D investment chosen by the other. Case I may involve the assumption that firm 2 cannot adjust its chosen R&D investment after observing firm 1's R&D investment.

In case II, firm 2 chooses its R&D investment *after* observing firm 1's R&D investment. This case also covers the situation in which firm 2 can adjust its chosen R&D investment – chosen before observing firm 1's R&D investment – after observing firm 1's R&D investment, and firm 1 is aware of this possibility.

The following game, game I, models case I. First, each firm chooses its R&D investment – that is, firm i chooses a value of x_i – *without* observing the rival's choice. Next, firm 1 discloses its R&D investment publicly, whereas firm 2 does not disclose its own R&D investment. As a result, firm 1 knows only its own new marginal production cost, while firm 2 knows the new marginal production costs of both firms. Finally, both firms choose their output levels simultaneously and independently.

Case II is modeled by the following game, game II. First, firm 1 chooses and discloses its R&D investment publicly. Next, *after* observing firm 1's R&D investment, firm 2 chooses its R&D investment but does not disclose it. Consequently, as in game I, firm 1 knows only its own new marginal production cost, while firm 2 knows the new marginal production costs of both firms. Finally, both firms choose their output levels simultaneously and independently.

Let $\pi_i(c_i)$ denote firm i's gross profits of producing q_i – without subtracting its cost of R&D investment – given its marginal production cost of c_i. Then firm i's gross profit function is

$$\pi_i(c_i) = (a - q_i - q_j - c_i)q_i \tag{1}$$

for $i, j = 1, 2$ with $i \neq j$, where q_j denotes firm j's output level.

Let $\Pi_i(x_i)$ denote firm i's profits when it chooses an R&D investment of x_i. Then firm i's profit function is

$$\Pi_i(x_i) \;=\; \pi_i(c^M - \delta x_i) \;-\; \gamma x_i^2/2, \tag{2}$$

where $\pi_i(c^M - \delta x_i)$ denotes firm i's gross profits – given its new marginal production cost of $(c^M - \delta x_i)$, which results from its R&D investment x_i.

We assume that all of the above is common knowledge between the firms.

3. Comparing the outcomes of the two games

In this section, we first obtain the equilibrium R&D investments, output levels, and profits for the firms, in both games I and II. Then, we compare the outcomes of game I with those of game II.

3.1. Game I

To obtain the equilibrium R&D investments, output levels, and profits of the firms in game I, we apply the solution technique for game I, as outlined in Appendix A1 of Baik and Lee (2025). We relegate the detailed analysis to Appendix A (see also Baik and Kim, 2025).

Let the superscript * indicate the outcomes of game I. Lemma 1 summarizes the outcomes of game I.

Lemma 1. (*a*) *In the equilibrium of game I, firm* 1 *chooses* $x_1^* = 4\delta(\gamma - \delta^2)(a - c^M)/Z$ *and* $q_1^* = 3\gamma(\gamma - \delta^2)(a - c^M)/Z$, *and firm* 2 *chooses* $x_2^* = \delta(3\gamma - 4\delta^2)(a - c^M)/Z$ *and* $q_2^* = \gamma(3\gamma - 4\delta^2)(a - c^M)/Z$, *where* $Z \equiv 9\gamma^2 - 14\gamma\delta^2 + 4\delta^4$.

(*b*) *The equilibrium profits of firm* 1 *and those of firm* 2 *are* $\Pi_1^* = \gamma(9\gamma - 8\delta^2)(\gamma - \delta^2)^2(a - c^M)^2/Z^2$ *and* $\Pi_2^* = \gamma(2\gamma - \delta^2)(3\gamma - 4\delta^2)^2(a - c^M)^2/2Z^2$, *respectively*.

It is straightforward to verify that, under the parameter assumptions in Section 2, the equilibrium values, x_i^* and q_i^*, in part (a) and Π_i^* in part (b), for $i = 1, 2$, are positive. Lemma 1 holds under the following additional assumption on the parameters (in addition to those in Section 2): Assume that $\gamma(9\gamma - 10\delta^2)c^M > 4\delta^2(\gamma - \delta^2)a$ or, equivalently, $(c^M/a) > \{4\delta^2(\gamma - \delta^2)/\gamma(9\gamma - 10\delta^2)\}$, which yields that $c^M - \delta x_1^* > 0$ and $c^M - \delta x_2^* > 0$.[6]

In the equilibrium of game I, firms 1 and 2 first choose x_1^* and x_2^*, respectively, each without observing the other firm's R&D investment. Next, firm 1 discloses its R&D investment to the public, whereas firm 2 does not disclose its own. As a result, firm 1 knows only its own new marginal production cost, $c^M - \delta x_1^*$, while firm 2 knows the new marginal production costs of both firms, $c^M - \delta x_1^*$ and $c^M - \delta x_2^*$. Finally, forming its belief x_2^* about firm 2's R&D investment – so that this belief is consistent with firm 2's equilibrium R&D choice – firm 1 chooses its equilibrium output level q_1^* (see Remark A1 in Appendix A). At the same time, knowing both firms' new marginal production costs, firm 2 chooses its equilibrium output level q_2^*.

Under the parameter assumptions specified in Section 2, together with the additional assumption stated below Lemma 1, one can readily verify that the following results hold: $x_1^* > x_2^*$, $q_1^* > q_2^*$, and $\Pi_1^* > \Pi_2^*$. These results can be explained as follows.

In game I, *ceteris paribus*, an increase in firm 1's R&D investment, x_1, raises firm 1's output level, $q_1(x_1, x_2^o)$, as given in (A2) in Appendix A, and reduces firm 2's output level, $q_2(x_1, x_2)$, as shown in (A3). In contrast, an increase in firm 2's R&D investment, x_2, increases firm 2's output level, $q_2(x_1, x_2)$, in (A3), while firm 1's output level, $q_1(x_1, x_2^o)$, in (A2) remains unchanged. More precisely, we have: $\partial q_1(x_1, x_2^o)/\partial x_1 = 2\delta/3$, $\partial q_2(x_1, x_2)/\partial x_1 = -\delta/3$, $\partial q_1(x_1, x_2^o)/\partial x_2 = 0$, and $\partial q_2(x_1, x_2)/\partial x_2 = 2\delta/3$. These asymmetric effects, together with the equilibrium condition that firm 1's belief about firm 2's R&D investment be consistent with firm 2's chosen R&D investment, lead to an equilibrium in which $\partial\Pi_1/\partial x_1 = \partial\Pi_2/\partial x_2 = 0$ when $x_1^* > x_2^*$. In other words, in equilibrium, firm i's marginal gross profits, $\partial\pi_i/\partial x_i$, for all $i = 1, 2$, are equal to its marginal cost, γx_i, when $x_1^* > x_2^*$ (see (A4) and (A6)).

Intuitively, firm 1 chooses a larger R&D investment than firm 2 because, due to its observability, an increase in its investment generates more favorable strategic effects in the subsequent output competition than a comparable increase by firm 2.

Next, consider the result that $q_1^* > q_2^*$. Since $x_1^* > x_2^*$, firm 1's new marginal production cost is lower than firm 2's: $c^M - \delta x_1^* < c^M - \delta x_2^*$. As a result, firm 1 gains a cost advantage in the subsequent output competition, which – together with firm 1's belief x_2^* about firm 2's R&D investment – leads to the result that $q_1^* > q_2^*$ (see (A2) and (A3)).

Finally, consider the result that $\Pi_1^* > \Pi_2^*$. Under the assumption that firm 1's belief about firm 2's R&D investment is consistent with firm 2's chosen R&D investment, firm 1's marginal gross profits, $\partial\pi_1/\partial x_1$, are greater than firm 2's, $\partial\pi_2/\partial x_2$, whereas both firms' marginal costs are the same, until their R&D investments reach x_2^*. Since $x_1^* > x_2^*$, this implies that $\Pi_1^* > \Pi_2^*$.

3.2. Game II

We view this game as the following two-stage game.[7] In the first stage, firm 1 chooses its R&D investment, and discloses it to the public. In the second stage, after observing firm 1's R&D investment, firm 2 chooses its R&D investment, but does not disclose it to the public; then both firms choose their output levels simultaneously and independently.

To obtain the equilibrium R&D investments, output levels, and profits of the firms in game II, we apply the solution technique for game II described in Appendix A2 of Baik and Lee (2025). The detailed analysis is provided in Appendix B.

Let the superscript ** indicate the outcomes of game II. Lemma 2 summarizes the outcomes of game II.

Lemma 2. (*a*) *In the equilibrium of game II, firm* 1 *chooses* $x_1^{**} = 2\delta(\gamma - \delta^2)(2\gamma - \delta^2)(a - c^M)/H$ *and* $q_1^{**} = \gamma(\gamma - \delta^2)(3\gamma - 2\delta^2)(a - c^M)/H$, *and firm* 2 *chooses* $x_2^{**} = \delta\{\gamma(3\gamma - 2\delta^2) - 2\delta^2(2\gamma - \delta^2)\}(a - c^M)/H$ *and* $q_2^{**} = \gamma\{\gamma(3\gamma - 2\delta^2) - 2\delta^2(2\gamma - \delta^2)\}(a - c^M)/H$, *where* $H \equiv \gamma(3\gamma - 2\delta^2)^2 - 2\delta^2(2\gamma - \delta^2)^2$.

(*b*) *The equilibrium profits of firm* 1 *and those of firm* 2 *are* $\Pi_1^{**} = \gamma(\gamma - \delta^2)^2(a - c^M)^2/H$ *and* $\Pi_2^{**} = \gamma(2\gamma - \delta^2)\{\gamma(3\gamma - 2\delta^2) - 2\delta^2(2\gamma - \delta^2)\}^2(a - c^M)^2/2H^2$, *respectively*.

It is straightforward to verify that, under the parameter assumptions in Section 2, the equilibrium values, x_i^{**} and q_i^{**}, in part (*a*) and Π_i^{**} in part (*b*), for $i = 1, 2$, are positive. Lemma 2 holds under the following additional assumption on the parameters (in addition to those in Section 2): Assume that $\gamma(9\gamma^2 - 16\delta^2\gamma + 6\delta^4)c^M > 2\delta^2(2\gamma^2 - 3\delta^2\gamma + \delta^4)a$ or, equivalently, $(c^M/a) > \{2\delta^2(2\gamma^2 - 3\delta^2\gamma + \delta^4)/\gamma(9\gamma^2 - 16\delta^2\gamma + 6\delta^4)\}$, which yields that $c^M - \delta x_1^{**} > 0$ and $c^M - \delta x_2^{**} > 0$.[8]

In the equilibrium of game II, firm 1 first chooses its R&D investment x_1^{**} and publicly discloses it. Next, after observing x_1^{**}, firm 2 chooses its R&D investment x_2^{**}, which it does not disclose. As a result, firm 1 observes only its own new marginal production cost, $c^M - \delta x_1^{**}$, whereas firm 2 observes the new marginal production costs of both firms, $c^M - \delta x_1^{**}$ and $c^M - \delta x_2^{**}$. Finally, firm 1 forms a belief about firm 2's R&D investment, x_2^{**}, and chooses its equilibrium output level q_1^{**}. At the same time, firm 2, knowing both firms' new marginal production costs, chooses its equilibrium output level q_2^{**}.

It is straightforward to verify that, under the parameter assumptions in Section 2 and the additional assumption stated below Lemma 2, the following results hold: $x_1^{**} > x_2^{**}$, $q_1^{**} > q_2^{**}$, and $\Pi_1^{**} > \Pi_2^{**}$. These results can be explained as follows.

In game II, firm 1 holds a strategic advantage as the first mover in determining its R&D investment, since firm 2 chooses its R&D investment after observing firm 1's choice. Note that, *ceteris paribus*, an increase in firm 1's R&D investment, x_1, reduces firm 2's R&D investment, $x_2(x_1)$, as shown in (B5) in Appendix B, raises firm 1's output level, $q_1(x_1)$, as given in (B6), and reduces firm 2's output level, $q_2(x_1)$, as shown in (B7), in the second-stage equilibrium. More precisely, we have: $dx_2(x_1)/dx_1 = -\delta^2/(3\gamma - 2\delta^2)$, $dq_1(x_1)/dx_1 = \delta(2\gamma - \delta^2)/(3\gamma - 2\delta^2)$, and $dq_2(x_1)/dx_1 = -\gamma\delta/(3\gamma - 2\delta^2)$. Given these effects, firm 1 increases its R&D investment until its marginal gross profits, $\partial\pi_1/\partial x_1$, equal its marginal cost, γx_1, (see (B8)). After observing firm

1's choice, x_1^{**}, firm 2 chooses its R&D investment, x_2^{**}, based on its reaction function (B5). This leads to the result that $x_1^{**} > x_2^{**}$.

Intuitively, firm 1 chooses a larger R&D investment than firm 2 for two reasons. First, firm 1 benefits from a first-mover advantage, as it discloses its R&D investment before firm 2 chooses its R&D investment. Second, because firm 1's investment is observable, an increase in its R&D investment generates more favorable strategic effects in the subsequent output competition than a comparable increase by firm 2.

Next, consider the result that $q_1^{**} > q_2^{**}$. Since $x_1^{**} > x_2^{**}$, firm 1's new marginal production cost is lower than firm 2's: $c^M - \delta x_1^{**} < c^M - \delta x_2^{**}$. This gives firm 1 a cost advantage in the subsequent output competition, and leads to the result that $q_1^{**} > q_2^{**}$.[9]

Finally, consider the result that $\Pi_1^{**} > \Pi_2^{**}$. Firm 1's strategic advantage as the first mover leads to the result that $x_1^{**} > x_2^{**}$. This implies that firm 1's cost of R&D investment, $\gamma(x_1^{**})^2/2$, is greater than firm 2's, $\gamma(x_2^{**})^2/2$. However, since $c^M - \delta x_1^{**} < c^M - \delta x_2^{**}$ and $q_1^{**} > q_2^{**}$, firm 1's gross profits, $\pi_1^{**}(c^M - \delta x_1^{**})$, exceed those of firm 2, $\pi_2^{**}(c^M - \delta x_2^{**})$ (see (1)). Despite this, the difference in the firms' gross profits outweighs the difference in their R&D costs, leading to the result that $\Pi_1^{**} > \Pi_2^{**}$.

3.3. Comparison of the outcomes of games I and II

Now, using Lemmas 1 and 2, we compare the outcomes of game I with those of game II. Recall that, in addition to the assumptions stated in Section 2, Lemmas 1 and 2 require further restrictions on the parameters, which are specified below each lemma. In particular, Lemma 1 holds when $(c^M/a) > \{4\delta^2(\gamma - \delta^2)/\gamma(9\gamma - 10\delta^2)\}$, and Lemma 2 holds when $(c^M/a) > \{2\delta^2(2\gamma^2 - 3\delta^2\gamma + \delta^4)/\gamma(9\gamma^2 - 16\delta^2\gamma + 6\delta^4)\}$. Now that $(c^M/a) > \{2\delta^2(2\gamma^2 - 3\delta^2\gamma + \delta^4)/\gamma(9\gamma^2 - 16\delta^2\gamma + 6\delta^4)\} > \{4\delta^2(\gamma - \delta^2)/\gamma(9\gamma - 10\delta^2)\}$, Lemmas 1 and 2 hold under Assumption 1.

Assumption 1. *We assume that* $\{2\delta^2(2\gamma^2 - 3\delta^2\gamma + \delta^4)/\gamma(9\gamma^2 - 16\delta^2\gamma + 6\delta^4)\} < (c^M/a) < 1$.

This assumption is not overly restrictive. It establishes a lower bound of (c^M/a), which is determined by the values of γ and δ. For instance, if $\gamma = 1$ and $\delta = 0.1$, the assumption implies that $(197.01/44203) < (c^M/a) < 1$.

Proposition 1 compares the outcomes of game I and game II. Recall that the superscripts * and ** denote the outcomes of game I and game II, respectively.

Proposition 1. (*a*) $x_1^* < x_1^{**}$ *and* $x_2^* > x_2^{**}$, (*b*) $q_1^* < q_1^{**}$ *and* $q_2^* > q_2^{**}$, *and* (*c*) $\Pi_1^* < \Pi_1^{**}$ *and* $\Pi_2^* > \Pi_2^{**}$.

The proof of Proposition 1 is provided in Appendix C. In game II, unlike in game I, firm 1 can commit in the first stage to its R&D investment, which is observable to firm 2. This commitment, along with its observability, gives firm 1 a first-mover advantage, leading to the results in part (*a*).

Part (*a*) of Proposition 1 is illustrated in Figure 1. In game I, when making its R&D investment decision, the reaction function of firm 1, given by (A5) in Appendix A, is represented by line I in the figure. The reaction function of firm 2, given by (A7) in Appendix A and modified using the equilibrium condition $x_2^o = x_2$, is represented by line II.[10] Hence, the firms' equilibrium R&D investments, x_1^* and x_2^*, are determined at point A in Figure 1, the intersection of lines I and II. In contrast, in game II, firm 1's first-mover advantage allows it to choose its R&D investment along line II in Figure 1 so as to maximize its profits. Firm 1 selects x_1^{**} at point B on line II, which lies to the right of point A, implyimg that $x_1^* < x_1^{**}$ and $x_2^* > x_2^{**}$.

Next, we explain the results for the firms' equilibrium output levels in part (*b*). In the equilibrium of game I, given the firms' equilibrium R&D investments, x_1^* and x_2^*, and under the equilibrium condition $x_2^o = x_2^*$, the reaction function of firm 1 in (A2) in Appendix A reduces to

$$q_1(x_1^*, x_2^*) \;=\; (a - c^M + 2\delta x_1^* - \delta x_2^*)/3, \tag{3}$$

which yields firm 1's equilibrium output level q_1^*. Similarly, the reaction function of firm 2 in (A3) in Appendix A reduces to

$$q_2(x_1^*, x_2^*) \;=\; (a - c^M + 2\delta x_2^* - \delta x_1^*)/3, \tag{4}$$

which yields firm 2's equilibrium output level q_2^*.

In the equilibrium of game II, given the firms' equilibrium R&D investments, x_1^{**} and x_2^{**}, and under the equilibrium condition $x_2^o = x_2^{**}$, the reaction function of firm 1 in (B1) in Appendix B reduces to

$$q_1(x_1^{**}, x_2^{**}) \;=\; (a - c^M + 2\delta x_1^{**} - \delta x_2^{**})/3, \tag{5}$$

which yields firm 1's equilibrium output level q_1^{**}. Similarly, the reaction function of firm 2 in (B2) in Appendix B reduces to

$$q_2(x_1^{**}, x_2^{**}) \;=\; (a - c^M + 2\delta x_2^{**} - \delta x_1^{**})/3, \tag{6}$$

which yields firm 2's equilibrium output level q_2^{**}.

Using the results in part (*a*), we find that firm 1's equilibrium output level in game I, q_1^* in (3), is lower than its equilibrium output level in game II, q_1^{**} in (5), whereas firm 2's equilibrium output level in game I, q_2^* in (4), is greater than its equilibrium output level in game II, q_2^{**} in (6).

Finally, we explain the results for the firms' equilibrium profits in part (*c*). In the equilibrium of game I, given the firms' equilibrium R&D investments, x_1^* and x_2^*, and imposing the equilibrium condition $x_2^o = x_2^*$, we obtain firm 1's equilibrium profits from (A4) in Appendix A:

$$\Pi_1^* \;=\; (q_1^*)^2 \;-\; \gamma(x_1^*)^2/2. \tag{7}$$

Similarly, we obtain firm 2's equilibrium profits from (A6) in Appendix A:

$$\Pi_2^* \;=\; (q_2^*)^2 \;-\; \gamma(x_2^*)^2/2. \tag{8}$$

In the equilibrium of game II, given the firms' equilibrium R&D investments, x_1^{**} and x_2^{**}, and imposing the equilibrium condition $x_2^{o} = x_2^{**}$, we obtain firm 2's equilibrium profits from (B3) in Appendix B:

$$\Pi_2^{**} = (q_2^{**})^2 - \gamma(x_2^{**})^2/2. \tag{9}$$

Given the firms' equilibrium R&D investments, x_1^{**} and x_2^{**}, we obtain firm 1's equilibrium profits from (B6) and (B8) in Appendix B:

$$\Pi_1^{**} = (q_1^{**})^2 - \gamma(x_1^{**})^2/2. \tag{10}$$

Using the results from parts (*a*) and (*b*), we observe that $(q_1^{*})^2$ and $\gamma(x_1^{*})^2/2$ in (7) are smaller than $(q_1^{**})^2$ and $\gamma(x_1^{**})^2/2$ in (10), respectively. However, because the increase in firm 1's equilibrium gross profits, $(q_1^{**})^2 - (q_1^{*})^2$, exceeds the increase in its equilibrium R&D investment cost, $\gamma(x_1^{**})^2/2 - \gamma(x_1^{*})^2/2$, firm 1's equilibrium profits in game I, Π_1^{*} in (7), is lower than its equilibrium profits in game II, Π_1^{**} in (10). In contrast, using the results from parts (*a*) and (*b*), we observe that $(q_2^{*})^2$ and $\gamma(x_2^{*})^2/2$ in (8) are greater than $(q_2^{**})^2$ and $\gamma(x_2^{**})^2/2$ in (9), respectively. However, because the decrease in firm 2's equilibrium gross profits, $\left|(q_2^{**})^2 - (q_2^{*})^2\right|$, exceeds the decrease in its equilibrium R&D investment cost, $\left|\gamma(x_1^{**})^2/2 - \gamma(x_1^{*})^2/2\right|$, firm 2's equilibrium profits in game I, Π_2^{*} in (8), is higher than its equilibrium profits in game II, Π_2^{**} in (9).

As discussed in Section 1, Baik and Lee (2020, 2025) consider two games – game I and game II – in a quantity-setting duopoly with managerial delegation, and show that the outcomes (specifically, the equilibrium contracts, output levels, and profits of the firms) are identical across the two games. This equivalence can be explained by the following observations. First, in both games, each manager faces the same information structure regarding the contracts chosen by the two owners when choosing the firm's output level. Consequently, for any given pair of contracts, the output levels chosen by each manager must be identical across the two games. Second, in both games, owner 2's contract choice is independent of owner 1's contract and does

not serve as a commitment device. As a result, owner 2 chooses the same equilibrium contract in both games, effectively inducing manager 2 to behave as a profit maximizer in the output competition. Given this, owner 1 also chooses the same equilibrium contract in both games.

4. Conclusions

We have formulated and analyzed two games – game I and game II – in a quantity-setting duopoly with R&D competition, and investigated whether these games lead to identical outcomes. Game I proceeds as follows. First, each firm chooses its R&D investment without observing the rival's choice. Then, firm 1 publicly discloses its R&D investment, while firm 2 does not disclose its own. Finally, both firms choose their output levels simultaneously and independently. Game II, by contrast, unfolds differently. First, firm 1 chooses and publicly discloses its R&D investment. After observing firm 1's R&D investment, firm 2 chooses its own R&D investment but does not disclose it. Finally, both firms choose their output levels simultaneously and independently.

In both games, each firm's R&D outcome – its resulting marginal production cost – is deterministically determined. As a result, when deciding on its R&D investment, each firm is certain of the marginal production cost it will incur. When choosing its output level, firm 2 is aware of firm 1's new marginal cost.

We have shown that the outcomes of game I differ from those of game II. Specifically, firm 1's equilibrium R&D investment, output level, and profits are all lower in game I than in game II. In contrast, firm 2's equilibrium R&D investment, output level, and profits are higher in game I than in game II. These differences arise because, in game II, firm 1 can commit to its R&D investment in the first stage, and this commitment is observable to firm 2. This ability to commit and disclose its R&D investment confers a first-mover advantage on firm 1.

Footnotes

1. One example is a duopoly with managerial delegation, in which two firm owners first choose delegation contracts independently, after which managers compete in quantities or prices under asymmetric information about those contracts. Another example is a duopoly with cost-reducing R&D investment, where firms first choose R&D investment levels independently and subsequently compete in quantities or prices under asymmetric information about their resulting production costs. A further example is a rent-seeking contest between two groups, in which members of each group first determine how to share the rent among themselves if they win, and then all players exert effort simultaneously and independently under asymmetric information about the groups' sharing rules.

2. Baik and Lee (2020) examine a quantity-setting duopoly with managerial delegation in which each firm *endogenously* decides whether to disclose the contract between its owner and manager. To analyze a situation in which one owner publicly discloses her chosen contract while the other owner does not, they consider two distinct games similar to those studied in Baik and Lee (2025).

3. Quadratic R&D cost functions are commonly used in the literature; see, for example, Ishida et al. (2011), Lin and Zhou (2013), Milliou and Pavlou (2013), and Chang and Ho (2014).

4. Milliou and Pavlou (2013), Chang and Ho (2014), Ishii (2017), and Jiang and Xiong (2025) assume that, after making their R&D investments, firms' new marginal production costs are deterministically determined.

5. It would be more appropriate to assume that the value of the parameter δ is much smaller than 0.5.

6. If $\gamma(9\gamma - 10\delta^2)c^M > 4\delta^2(\gamma - \delta^2)a$, then $(c^M - \delta x_1^*) > 0$. If $\gamma(9\gamma - 11\delta^2)c^M > \delta^2(3\gamma - 4\delta^2)a$, then $(c^M - \delta x_2^*) > 0$. Since $(c^M/a) > \{4\delta^2(\gamma - \delta^2)/\gamma(9\gamma - 10\delta^2)\} > \{\delta^2(3\gamma - 4\delta^2)/\gamma(9\gamma - 11\delta^2)\}$, it follows that, if $(c^M/a) > \{4\delta^2(\gamma - \delta^2)/\gamma(9\gamma - 10\delta^2)\}$, then $c^M - \delta x_1^* > 0$ and $c^M - \delta x_2^* > 0$.

7. Alternatively, we can solve game II by viewing it as the following two-stage game. In the first stage, firm 1 chooses its R&D investment and discloses it to the public. In the second stage, after observing firm 1's R&D investment, firm 1 chooses its output level without observing firm 2's R&D investment or output choice; firm 2 chooses its R&D investment, and then chooses its output level without observing firm 1's output choice. Applying the solution technique outlined in Baik and Lee (2012), we obtain exactly the same outcomes as those reported in Lemma 2.

8. If $\gamma(9\gamma^2 - 16\delta^2\gamma + 6\delta^4)c^M > 2\delta^2(2\gamma^2 - 3\delta^2\gamma + \delta^4)a$, then $(c^M - \delta x_1^{**}) > 0$. If $\gamma(9\gamma^2 - 17\delta^2\gamma + 6\delta^4)c^M > \delta^2(3\gamma^2 - 6\delta^2\gamma + 2\delta^4)a$, then $(c^M - \delta x_2^{**}) > 0$. Since $(c^M/a) > \{2\delta^2(2\gamma^2 - 3\delta^2\gamma + \delta^4)/\gamma(9\gamma^2 - 16\delta^2\gamma + 6\delta^4)\} > \{\delta^2(3\gamma^2 - 6\delta^2\gamma + 2\delta^4)/\gamma(9\gamma^2 - 17\delta^2\gamma + 6\delta^4)\}$, it follows that, if $(c^M/a) > \{2\delta^2(2\gamma^2 - 3\delta^2\gamma + \delta^4)/\gamma(9\gamma^2 - 16\delta^2\gamma + 6\delta^4)\}$, then $c^M - \delta x_1^{**} > 0$ and $c^M - \delta x_2^{**} > 0$.

9. Using (B6) and (B7), we find that $q_1(x_1) > q_2(x_1)$ in the second-stage equilibrium.

10. Given the equilibrium condition that $x_2^o = x_2$, expression (A7) in Appendix A reduces to

$$x_2(x_1) = \delta(a - c^M - \delta x_1)/(3\gamma - 2\delta^2),$$

which is the same as expression (B5) in Appendix B.

Appendix A: Analysis of game I

To solve this game, we proceed in three steps. First, we analyze the firms' decisions in choosing their output levels. Next, we examine their decisions in choosing R&D investments. Finally, using the results from these two steps, we obtain the firms' equilibrium R&D investments, output levels, and profits.

The firms' decisions in choosing their output levels

We begin by considering firm i's decision on its output level, for $i = 1, 2$. After observing its new marginal production cost ($c^M - \delta x_i$), firm i seeks to maximize $\pi_i(c^M - \delta x_i)$ in (1) over q_i, taking the output level q_j of firm j as given, for $j = 1, 2$ with $i \neq j$. From the first-order condition for maximizing $\pi_i(c^M - \delta x_i)$, we obtain the following reaction function for firm i:

$$q_i(q_j; x_i) = (a - c^M + \delta x_i)/2 - q_j/2. \tag{A1}$$

The objective function π_i is strictly concave in q_i, and thus the second-order condition for maximizing π_i is satisfied.

Next, we further analyze the firms' output decisions. Firm 1 knows its own reaction function in (A1) for its R&D investment x_1: $q_1(q_2; x_1) = (a - c^M + \delta x_1)/2 - q_2/2$. Given its belief x_2^o about firm 2's R&D investment, firm 1 infers firm 2's reaction function: $q_2(q_1; x_2^o) = (a - c^M + \delta x_2^o)/2 - q_1/2$. Using these two reaction functions, we determine firm 1's output level at their intersection, and, in turn, obtain the following reaction function for firm 1:

$$q_1(x_1, x_2^o) = (a - c^M + 2\delta x_1 - \delta x_2^o)/3. \tag{A2}$$

By contrast, because firm 2 knows the new marginal production costs of both firms, it knows firm 1's reaction function and its own reaction function in (A1). Using these two reaction functions, we determine firm 2's output level at their intersection, and, in turn, obtain the following reaction function for firm 2:

$$q_2(x_1, x_2) \;=\; (a - c^M + 2\delta x_2 - \delta x_1)/3. \tag{A3}$$

The firms' decisions in choosing their R&D investments

We consider firm 1's decision on its R&D investment. Given x_2, firm 1 seeks to maximize its profits in (2) with respect to x_1, taking into account the firms' reaction functions, (A2) and (A3). That is, it chooses x_1 to maximize

$$\begin{aligned}\Pi_1(x_1, q_1(x_1, x_2^{\mathrm{o}}), q_2(x_1, x_2)) \;=\; & (a - c^M + 2\delta x_1 - 2\delta x_2 + \delta x_2^{\mathrm{o}}) \\ & \times (a - c^M + 2\delta x_1 - \delta x_2^{\mathrm{o}})/9 \;-\; \gamma x_1^2/2.\end{aligned} \tag{A4}$$

The quadratic R&D cost function, together with the assumptions $0 < \delta < 0.5$ and $\gamma \geq 1$, implies that Π_1 is strictly concave in x_1, and thus the second-order condition for maximizing Π_1 is satisfied. From the first-order condition for maximizing Π_1 in (A4), we obtain the following reaction function for firm 1:

$$x_1(x_2; x_2^{\mathrm{o}}) \;=\; 4\delta(a - c^M - \delta x_2)/(9\gamma - 8\delta^2). \tag{A5}$$

Next, we consider firm 2's decision on its R&D investment. Given x_1, firm 2 seeks to maximize its profits in (2) with respect to x_2, taking into account the firms' reaction functions, (A2) and (A3). That is, it chooses x_2 to maximize

$$\begin{aligned}\Pi_2(x_2, q_1(x_1, x_2^{\mathrm{o}}), q_2(x_1, x_2)) \;=\; & (a - c^M - \delta x_1 + \delta x_2 + \delta x_2^{\mathrm{o}}) \\ & \times (a - c^M + 2\delta x_2 - \delta x_1)/9 \;-\; \gamma x_2^2/2.\end{aligned} \tag{A6}$$

It is straightforward to verify that Π_2 is strictly concave in x_2, and thus the second-order condition for maximizing Π_2 is satisfied. From the first-order condition for maximizing Π_2 in (A6), we obtain the following reaction function for firm 2:

$$x_2(x_1; x_2^{\mathrm{o}}) \;=\; \delta(3a - 3c^M - 3\delta x_1 + 2\delta x_2^{\mathrm{o}})/(9\gamma - 4\delta^2). \tag{A7}$$

The firms' equilibrium R&D investments, output levels, and profits

First, using the firms' reaction functions, (A5) and (A7), and the equilibrium condition that $x_2^o = x_2$ (see Remark A1), we obtain the equilibrium R&D investments, x_1^* and x_2^*, of the firms. Then, substituting $x_2^o = x_2^*$, $x_1 = x_1^*$, and $x_2 = x_2^*$ into firm 1's reaction function (A2) and firms 2's reaction function (A3), we obtain the equilibrium output levels, q_1^* and q_2^*, of the firms. Finally, substituting $x_2^o = x_2^*$, $x_1 = x_1^*$, and $x_2 = x_2^*$ into (A4) and (A6), we obtain the equilibrium profits, Π_1^* and Π_2^*, of the firms.

Remark A1. *We impose the equilibrium condition or requirement that firm* 1*'s belief* x_2^o *about firm* 2*'s R&D investment be consistent with firm* 2*'s chosen R&D investment* x_2*:* $x_2^o = x_2$*. Accordingly, in equilibrium, firm* 1*'s belief about firm* 2*'s R&D investment is* x_2^**.*

Appendix B: Analysis of game II

To solve this two-stage game, we proceed in three steps. First, we analyze the subgames which start at the second stage of the game. Next, we analyze the first stage in which firm 1 chooses its R&D investment. Finally, using the findings in these two steps, we obtain the firms' equilibrium R&D investments, output levels, and profits.

Analyzing the subgames starting at the second stage

We begin by considering firm *i*'s decision on its output level, for $i = 1, 2$. Firm *i* has the same information structure as in game I regarding the firms' chosen R&D investments when choosing its output level. Accordingly, the reaction functions for firms 1 and 2 are the same as those in (A2) and (A3), respectively:

$$q_1(x_1, x_2^o) = (a - c^M + 2\delta x_1 - \delta x_2^o)/3 \tag{B1}$$

and

$$q_2(x_1, x_2) = (a - c^M + 2\delta x_2 - \delta x_1)/3. \tag{B2}$$

Next, we consider firm 2's decision on its R&D investment. Knowing x_1, firm 2 seeks to maximize its profits in (2) with respect to x_2, taking into account the firms' reaction functions, (B1) and (B2). That is, it chooses x_2 to maximize

$$\Pi_2(x_2, q_1(x_1, x_2^o), q_2(x_1, x_2)) = (a - c^M - \delta x_1 + \delta x_2 + \delta x_2^o) \times (a - c^M + 2\delta x_2 - \delta x_1)/9 - \gamma x_2^2/2. \quad \text{(B3)}$$

It is straightforward to verify that Π_2 is strictly concave in x_2, and thus the second-order condition for maximizing Π_2 is satisfied. From the first-order condition for maximizing Π_2 in (B3), we obtain the following reaction function for firm 2:

$$x_2(x_1; x_2^o) = \delta(3a - 3c^M - 3\delta x_1 + 2\delta x_2^o)/(9\gamma - 4\delta^2). \quad \text{(B4)}$$

Now we obtain the equilibrium of the subgame induced by firm 1's R&D investment x_1. First, using firm 2's reaction function (B4) and the equilibrium condition that $x_2^o = x_2$, we obtain the following reaction function for firm 2:

$$x_2(x_1) = \delta(a - c^M - \delta x_1)/(3\gamma - 2\delta^2). \quad \text{(B5)}$$

Then, substituting $x_2^o = x_2$ and (B5) into firms 1's reaction function (B1) and firm 2's reaction function (B2), we obtain the following reaction functions for the firms:

$$q_1(x_1) = \{(\gamma - \delta^2)(a - c^M) + \delta(2\gamma - \delta^2)x_1\}/(3\gamma - 2\delta^2) \quad \text{(B6)}$$

and

$$q_2(x_1) = \gamma(a - c^M - \delta x_1)/(3\gamma - 2\delta^2). \quad \text{(B7)}$$

Analyzing the first stage

Consider the first stage in which firm 1 chooses its R&D investment x_1. Having perfect foresight about $q_1(x_1)$ in (B6) and $q_2(x_1)$ in (B7) for any value of x_1, firm 1 seeks to maximize its profits in (2) with respect to x_1. That is, it chooses x_1 to maximize

$$\Pi_1(x_1, q_1(x_1), q_2(x_1)) = \{a - q_1(x_1) - q_2(x_1) - (c^M - \delta x_1)\}q_1(x_1) - \gamma x_1^2/2 \quad \text{(B8)}$$

$$= \{q_1(x_1)\}^2 - \gamma x_1^2/2.$$

The second-order condition for maximizing Π_1 in (B8) is satisfied because $\partial^2\Pi_1/\partial x_1^2 = 2\delta^2(2\gamma-\delta^2)^2/(3\gamma-2\delta^2)^2 - \gamma < 0$ under the assumed parameter restrictions. From the first-order condition for maximizing Π_1 in (B8) with respect to x_1, we obtain the equilibrium R&D investment of firm 1:

$$x_1^{**} = 2\delta(\gamma-\delta^2)(2\gamma-\delta^2)(a-c^M)/\{\gamma(3\gamma-2\delta^2)^2 - 2\delta^2(2\gamma-\delta^2)^2\}.$$

Equilibrium R&D investments, *output levels*, *and profits*

Substituting $x_1 = x_1^{**}$ into firm 2's reaction function (B5), we obtain the equilibrium R&D investment x_2^{**} of firm 2. Substituting $x_1 = x_1^{**}$ into firm 1's reaction function (B6), and firm 2's reaction function (B7), we obtain the equilibrium output levels, q_1^{**} and q_2^{**}, of the firms. Finally, substituting $x_2^o = x_2^{**}$, $x_1 = x_1^{**}$, and $x_2 = x_2^{**}$ into (B3) and (B8), we obtain the equilibrium profits, Π_1^{**} and Π_2^{**}, of the firms.

Appendix C: Proof of Proposition 1

It is straightforward to verify parts (*i*) through (*v*) of Proposition 1. We now provide the proof of part (*vi*).

Recall that $\Pi_2^* = \gamma(2\gamma-\delta^2)(3\gamma-4\delta^2)^2(a-c^M)^2/2Z^2$ and $\Pi_2^{**} = \gamma(2\gamma-\delta^2)\{\gamma(3\gamma-2\delta^2) - 2\delta^2(2\gamma-\delta^2)\}^2(a-c^M)^2/2H^2$, where $Z \equiv 9\gamma^2 - 14\gamma\delta^2 + 4\delta^4$ and $H \equiv \gamma(3\gamma-2\delta^2)^2 - 2\delta^2(2\gamma-\delta^2)^2$.

We have then:

$$\begin{aligned}
\Pi_2^* - \Pi_2^{**} &= (\gamma/2)(2\gamma-\delta^2)(a-c^M)^2[(3\gamma-4\delta^2)^2/Z^2 \\
&\qquad - \{\gamma(3\gamma-2\delta^2) - 2\delta^2(2\gamma-\delta^2)\}^2/H^2] \\
&= (\gamma/2Z^2H^2)(2\gamma-\delta^2)(a-c^M)^2[(3\gamma-4\delta^2)^2H^2 \\
&\qquad - \{\gamma(3\gamma-2\delta^2) - 2\delta^2(2\gamma-\delta^2)\}^2Z^2] \\
&= (2\gamma^2\delta^4/Z^2H^2)(2\gamma-\delta^2)(a-c^M)^2\, U,
\end{aligned}$$

where $U \equiv 27\gamma^5 - 123\gamma^4\delta^2 + 211\gamma^3\delta^4 - 168\gamma^2\delta^6 + 61\gamma\delta^8 - 8\delta^{10}$. To prove that $\Pi_2^* > \Pi_2^{**}$, it suffices to show that $U > 0$. This is shown below.

(a) We have:

$$\partial U/\partial\gamma \;=\; \gamma^3(135\gamma - 492\delta^2) \;+\; \gamma\delta^4(633\gamma - 336\delta^2) \;+\; 61\delta^8 \;>\; 0$$

for $0 < \delta < 0.5$. Hence, U is minimized when $\gamma = 1$.

(b) Let $U(\gamma = 1)$ denote the value of U evaluated at $\gamma = 1$. Then, we have: $U(\gamma = 1) = 27 - 123\delta^2 + 211\delta^4 - 168\delta^6 + 61\delta^8 - 8\delta^{10}$. Since $dU(\gamma = 1)/d\delta = -246\delta + 844\delta^3 - 1008\delta^5 + 488\delta^7 - 80\delta^9 < 0$, $U(\gamma = 1)$ is decreasing as δ approaches 0.5 from below.

(c) The value of $U(\gamma = 1)$ evaluated at $\delta = 0.5$ is positive.

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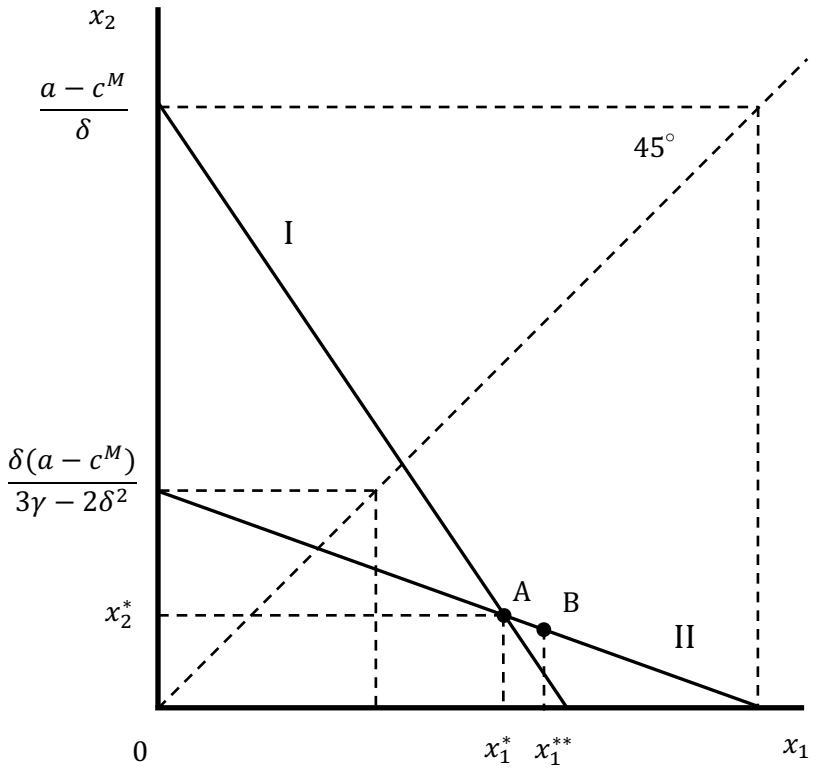

Figure 1. The Equilibrium R&D Investments