Bae, Chankwon

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R&D Spillovers with Endogenous Absorptive Capacity: Lessons for Developing Countries

Chankwon Bae*
Korea Institute for International Economic Policy
ckbae@kiep.go.kr

This paper analyzes the role of absorptive capacity in R&D spillovers through strategic R&D investments in a game-theoretic framework. In the model, a firm's effective R&D is composed of idiosyncratic R&D, which produces its own innovations, and identical R&D, which improves absorptive capacity. The model shows that in the presence of absorptive capacity firms have a tendency to underinvest (overinvest) in idiosyncratic (identical) R&D relative to the social optimum. As the spillover becomes larger, firms decrease their own R&D while they become more inclined towards strategic exploitation of rivals' efforts. Since the former effect overpowers the latter, the total amount of R&D decreases as the spillover increases. This is socially undesirable, providing a potential justification for a governmental subsidy for idiosyncratic R&D and a tax on identical R&D. The findings may have important implications for newly industrialized or emerging countries that consider a redirection of national R&D policy and intellectual property rights (IPR) regime.

Keywords: Absorptive Capacity, R&D, Spillovers
JEL Classification: L13, O31, O32, O38

I. INTRODUCTION

Technological advantage is one of the key factors to guarantee competitive advantage and, by extension, business success. This is the reason why firms engage in research and development (R&D). Therefore, a vast literature has been devoted to the discussion of firms' R&D activities. Spencer and Brander (1983) pioneer the model of multiple stage strategic investments as a tool to analyze how a firm's R&D investment increases its profits, thereby increasing its market share at the expense

* Korea Institute for International Economic Policy (KIEP), National Research Complex, Sicheongdaero, Sejong-si 30147, Korea
e-mail: ckbae@kiep.go.kr, Phone: +82-2-3460-1208, Fax: +82-2-3460-1077

of its rival. It is assumed that R&D is undertaken before the production of its associated output and firms anticipate the effect of R&D on the output share. R&D serves as a commitment or credible threat in their model. Hence the game naturally results in overinvesting in R&D relative to the social-cost minimizing level, analogously to the prisoner's dilemma, and the government has an incentive to impose taxes on R&D.

As seen in Spencer and Brander (1983), the strategic interaction between firms plays a crucial role in firms' decision on the levels of their output and R&D. The strategic behavior, however, is not a single factor determining market outcome. The new information created by a firm's R&D cannot be exclusively possessed by the firm because R&D has partly the nature of a public good. In reality, there exist numerous channels through which the information is spilled out. According to Mansfield's (1985) empirical study, detailed information concerning a new product and process generally ends up in the hands of rivals within a year, through input suppliers and customers, patent disclosures, reverse engineering, professional meetings and informal communications networks among engineers and scientists, and movement of personnel from one firm and another. It is especially true in the context of developing countries with weak intellectual property rights (IPR) protection. Since Spencer and Brander's seminal work, many subsequent modifications have been developed to better reflect this characteristic of R&D. These models are different in detail, but common in the fundamental structure. They consider a firm's R&D efforts imperfectly appropriable and thus the full or partial information on the firm's R&D results is leaked out to rivals. The degree of these spillovers is formalized by the spillover parameter with a range [0, 1]. In the presence of spillovers, firms have a tendency to free-ride on rivals when they make an R&D investment decision. This leads the firms to underinvest in R&D.[1] As a result, whether firms overinvest or underinvest in R&D depends on the relative magnitude of the conflicting forces of firms' strategic actions and the spillovers. The conclusion is made, not so surprisingly, as follows: when the spillovers are sufficiently large (small), firms underinvest (overinvest) in R&D and thus a R&D subsidy (tax) can be justified.[2]

Most of the existing literature, however, treats the R&D spillovers as virtually

[1] See d'Aspremont and Jacquemin (1988), De Bondt (1996), Amir et al. (2000).
[2] See Qui and Tao (1998), Leahy and Neary (1999), Kang (2006), Liao (2007).

exogenous. They assume that the level of R&D spillovers is influenced by institutional factors such as protection of IPR.[3] Although some studies try to endogenize the spillover by treating the IPR regime as a policy choice,[4] it is not purely endogenous in a sense that firms may still access a revealed portion of the new knowledge generated by rivals' R&D efforts costlessly and use it immediately to reduce their production costs. It seems somewhat odd that the amount of spillover from one to the other is treated as exogenous. In reality, the spillover is not actually acquired costlessly, but instead depends on firms' ability to evaluate and utilize outside knowledge. Cohen and Levinthal (1989) call it "absorptive capacity". More exactly, they define absorptive capacity as an ability to recognize the value of new external knowledge, assimilate it, and apply it to commercial ends (Cohen and Levinthal, 1990).

However, technological knowledge which enters the public domain has typically been regarded as a free good. Even though the knowledge is a public good, there are some costs in processing it. The classic economic literature argues that these costs are relatively small compared to the costs of inventing new technology.[5] However, Cohen and Levinthal (1989) assert that these costs are not inherently small, but rather are determined by the amount of related knowledge that firms have, and may be substantial in the long run. They stress that firms cannot passively assimilate external knowledge, and instead should invest in their own R&D as a basic source of knowledge to absorb the R&D results of their rivals. This is the so-called "second face" of R&D. In this sense, absorptive capacity is endogenous and so are spillovers.

Although the importance of absorptive capacity has gained immense attention, studies that incorporate absorptive capacity into the model of strategic R&D investments are rare. Beginning with Kamien and Zang (2000), only a few studies have tackled this problem. These studies divide R&D approaches of firms into two categories, narrow (or firm-specific) and broad (or identical). The intuition is that in the presence of R&D leakage, firms may choose narrow approaches to

[3] Firms can internalize the spillover by forming a research joint venture. In this case the spillover parameter may be set to be one. The issue on a joint venture may be another topic for future research. In this study I restrict my interest only to the non-cooperative (or competitive) R&D game.

[4] See Poyago-Theotoky (1999), Kang (2006), Liao (2007).

[5] See Arrow (1962), Hamberg (1963), Müller (1962) and Nelson (1959).

offset exogenous spillovers, while they may choose broad approaches to develop connectedness to external sources of knowledge, especially when there is no great danger that they are of benefit to rivals (Wiethaus, 2005). This classification of R&D may more or less correspond to that of the OECD. The OECD manual for surveys on R&D broadly distinguishes R&D into basic research and applied research. According to Cassiman et al. (2002) and Hammerschmidt (2009), basic research may be interpreted as broad R&D to build up absorptive capacity, as it allows firms to learn from knowledge that is externally available and, on the other hand, applied research may be understood as narrow R&D to generate firm-specific innovations. However, these links are highly ambiguous, and opposite links may look more reasonable sometimes. The important thing is that this dichotomy between the two research categories may fit reality to some extent.

The models of strategic R&D investments vary with how to apply these two research components to effective research, consisting of their own research and exogenous spillovers from rivals. Kamien and Zang (2000), as a pioneer of the endogenous absorptive capacity model, introduce a research approach choice variable with a range of [0, 1]. If this variable is one (zero) as an extreme case, then it corresponds to a strictly narrow (broad) approach. The game is composed of three stages, including a first stage where two firms simultaneously choose their R&D approaches, a second stage where they simultaneously choose their R&D expenditures, and a third stage where they simultaneously choose their output levels in Cournot competition. The equilibria of this game appear at the extremes, that is to say, in the presence of exogenous spillovers the firms only choose purely firm-specific R&D approaches to secure perfect appropriability of their R&D investments, while they choose broad R&D approaches only if there are no exogenous spillovers. Kaiser (2002a) develops the results of Kamien and Zang (2000) by providing various comparative statics. The main result is that a decrease in research generality leads to an increase in R&D spending when the R&D approach is sufficiently broad or if R&D expenditures are sufficiently high. In particular, empirically testable hypotheses are derived from the theoretical model, which are tested using German service sector data in Kaiser (2002b). Contrary to the findings by Kamien and Zang (2000), Wiethaus (2005) shows that firms may also adopt broad research approaches in the competitive case.[6] The basic setting of his model is analogous to Kamien and Zang (2000), but slightly differs in the definition of effective R&D. Kamien and Zang (2000) assume that a firm's effective R&D is homogenous of degree one in its own R&D. An increase in its own R&D raises the amount of spillover from the rival's R&D. On the other hand, in Wiethaus' (2005) model, the spillover is determined by its choice of R&D approaches and the rival's R&D investment, but not by the amount of its own R&D investment. This difference might result in the distinction between the two conclusions.

Grünfeld (2003) and Hammerschmidt (2009) adopt a different approach from the studies above. Grünfeld (2003) defines a spillover variable as a function of its own R&D investment and shows that the effect on absorptive capacity of its own R&D does not necessarily drive up the incentive to invest in R&D. Hammerschmidt (2009) distinguishes explicitly between investments in narrow and broad R&D in defining effective R&D. Firms invest both in firm-specific and absorptive capacity at the same time. The finding is that firms invest more in absorptive capacity when the exogenous spillover parameter is higher.

In this study I develop a non-cooperative R&D investments model with endogenous absorptive capacity. I address the question about how R&D spillovers affect strategic R&D activities of firms in the presence of absorptive capacity and derive implications for government policies. Following the previous literature, I define two different components of R&D, investment in idiosyncratic research and investment in absorptive capacity. In the Kamien and Zang (2000) types of models, it seems somewhat awkward that the decisions on the amount of R&D expenditures and R&D approaches are made at separate stages because both decisions should affect the level of absorptive capacity. If a firm's own R&D investment is dropped from the spillover term of effective R&D as in Wiethaus (2005), the absorptive capacity is determined solely in the first stage. However, this is also awkward. In Grünfeld (2003), the spillover variable is described as the sum of exogenous spillover parameter and absorptive capacity. It implies that the spillover can be realized even if there is no investment in absorptive capacity.

[6] He argues that a firm gains from the adoption of a broader R&D approach as long as its own expenditures are not too high in proportion to its rival's R&D. From the rival's point of view, a broader R&D approach implies lower appropriability and thus reduces the profitability of R&D investments.

This is contradictory to the idea of absorptive capacity. Hence I assume that firms invest in the two types of R&D in the same stage, as suggested in Hammerschmidt (2009). Idiosyncratic research directly reduces one's own marginal cost, while its results leak out to the public domain very quickly and thus may help reduce the rival's marginal cost. Broad research indirectly reduces the marginal cost by enhancing the ability to assimilate and exploit externally available technological information. Since the model is set up as a Cournot duopoly, carrying out broad R&D is equivalent to investing in research projects identical to a rival's.

Unlike previous studies, the model is described with general functional forms for flexibility in its application. In particular, the assumption of perfect substitution of products is relaxed to allow for more flexible market structure. Moreover, it is assumed that the actual R&D spillover rate is determined not only by regulatory factors, as usual, but also by technological similarity between firms. At the extreme end, where the two firms produce completely different products, it implies that there is nothing to learn from each other and consequently the spillover term should be zero. As a more important innovation, this study includes the government sector in the model to examine what should be the government's role in the presence of the two types of R&D and discusses how the existence of spillover and absorptive capacity affects firms' strategic motive for R&D investments in analyzing the results of the models.

The game proceeds along the framework of Spencer and Brander (1983) as follows: in the first stage of the game firms simultaneously choose the level of R&D and makes decisions as to how to balance it between the two types of R&D. In the second stage firms observe the results of the first stage and engage in Cournot competition. The game is solvable with backward induction to obtain a sub-game perfect Nash equilibrium (SPNE). Finally, I introduce the role of government into the model. This expands the game to three-stages. In the first stage the government announces its subsidy (tax, if negative) rates for the two types of R&D. In the second and third stage firms decide their R&D and output levels respectively, responding to the government policies.

The rest of this paper is organized as follows. The next section describes a spillover model that allows for absorptive capacity. In particular the market demand is characterized by a general functional form rather than the simplest linear form. Sections III and IV provide equilibrium output and R&D investment solutions respectively for the non-cooperative symmetric game and present comparative static analyses. Section V discusses optimal R&D policies introducing the government sector in the model. Section VI shows an example of a simulation. Finally, section VII summarizes the findings and makes concluding remarks.

II. THE MODEL

I suppose that there are two one-product firms producing product *i* and *j* respectively in a market. The firms produce differentiated products and compete by setting quantity. Demand for the goods is given by the general inverse demand function:

$$p_i = p(q_i + \theta q_j),\ p_i' < 0, \tag{2. 1}$$

where p_i is the price of product *i*, and q_i and q_j denote the quantity of product *i* and *j* respectively. The parameter θ represents a measure of substitutability of the two goods, ranging [0, 1]. If $\theta = 0$, the two varieties are independent of each other in demand. As θ approaches one, the varieties become closer and closer substitutes, and they all become perfect substitutes when $\theta = 1$. I assume that p_i is decreasing and is twice continuously differentiable, with $p_i'' q_i + p_i' < 0$,[7] as usual.

Initially the firms have a constant and identical marginal cost, which means that it is independent of the production level. They can reduce their marginal cost through investing in R&D as the game progresses. The assumption is that the firms will invest in two types of R&D, idiosyncratic (firm-specific) and identical (broad), as in Hammerschmidt (2009). This classification reflects the nature of R&D, which not only generates a firm's own innovations but also improves the ability to absorb the knowledge transferred from its rival. In other words, each firm lowers its marginal cost by conducting its own research and at the same time

[7] This assumption holds in most cases: in a linear demand with $p_i = a - b(q_i + \theta q_j)$, $p_i'' q_i + p_i' = -b < 0$, in a concave demand with $p_i = a - b(q_i + \theta q_j)^2$, $p_i'' q_i + p_i' = -2b(2q_i + \theta q_j) < 0$, and finally in a convex demand with $p_i = a - b\ \ln(q_i + \theta q_j)$, $p_i'' q_i + p_i' = -b\theta q_j / (q_i + \theta q_j)^2 < 0$.

by enhancing its absorptive capacity to effectively imitate the rival's successful innovations.

The results of idiosyncratic research are leaked to the rival at a rapid rate through various channels as revealed by Mansfield's (1985) empirical work. It is assumed that a firm's own successful innovations flow out to the public domain at a rate of β. Consequently, the effective R&D of firm *i* is characterized by

$$x_i = x_i^s + \gamma(x_i^t)\beta\varphi x_j^s, \tag{2. 2}$$

where $i, j = 1, 2$ and $i \neq j$. x_i^s and x_i^t are the investments in idiosyncratic and identical research respectively. $\gamma(\cdot)$ describes absorptive capacity of firm *i* as a function of x_i^t and is placed in the range of [0, 1] for all x_i^t. As firm *i* increases x_i^t, the level of its absorptive capacity should also increase, but at a decreasing rate due to the property of diminishing returns to investment. Hence it is assumed that $\gamma(\cdot)$ is twice continuously differentiable, increasing, and strictly concave in x_i^t, i.e. $\gamma' > 0$ and $\gamma'' < 0$ for all x_i^t. Furthermore, it is required that a firm cannot realize the spillovers from the rival if it does not invest in x_i^t. As a firm increases x_i^t, it can approach full appropriability of spillovers, while the marginal productivity of x_i^t nears zero as x_i^t approaches infinity. Additionally, the following conditions need to be assumed: $\gamma(0) = 0, \gamma'(0) = \infty,$ and $\gamma'(\infty) = 0.$ As a result, if $\gamma(x_i^t) = 1,$ then the R&D spillovers are costless to obtain, and on the other hand, $\gamma(x_i^t) < 1$ suggests the absorptive capacity case of R&D spillovers.

The parameter β is exogenously determined by regulatory factors such as intellectual rights protection and satisfies the range of [0, 1]. In addition, I consider that it should be easier for a firm to utilize its rival's successful innovations when they produce technologically similar products. The technological proximity between the two firms is captured by the parameter φ. As their technologies become more substitutable, the firms can internalize the spillover from each other at a lower cost. If β or φ is set to be zero, then the rival's unique knowledge is not appropriable, while it is perfectly accessible only if the two have attained unity, but not necessarily used because absorptive capacity itself may be costly. As a consequence, the actual strength of the spillover is determined endogenously by the level of absorptive capacity in the model.

Assuming that the effective R&D of equation (2. 2) reduces the unit cost of production through the knowledge production function *f*, then the marginal cost of firm *i* is given by

$$MC_i = c - f(x_i), \tag{2. 3}$$

where c is the initial marginal cost, which is constant, and is large enough such that MC_i is positive, which means $f(x_i) < c$. Similarly with the properties of γ, it is assumed that $f' > 0$ and $f'' < 0$ for all x_i and $f'(\infty) = 0$ and $f'(0) = \infty$.

The model describes the interactions between two firms using a two-stage, one-shot non-cooperative game. In the first stage of the game, each firm simultaneously chooses how much to spend on each R&D. In the second stage, each firm observes the level and combination of the rival's R&D investments and engages in Cournot competition, q_i and q_j. Since R&D projects are launched prior to the production of output and the firms anticipate impacts from R&D on their output and profit, R&D acts as a credible threat in this game. The second stage solution is written as a function of the optimal levels of the two types of R&D given in the preceding stage. Hence the subgame perfect equilibrium outputs and R&D investments are seen retreating from the second stage to the first stage. I focus on symmetric solutions to simplify the analysis.

III. SECOND STAGE (OUTPUT STAGE)

Each firm seeks to maximize its profit function, which is given by

$$\pi_i = [p_i(q_i + \theta q_j) - c + f(x_i)]q_i - (x_i^s + x_i^t), \tag{3. 1}$$

where $i, j = 1, 2$ and $i \neq j$, and $f(x_i) = f(x_i^s + \gamma(x_i^t)\beta\varphi x_j^s)$. Given the pairs of the two types of R&D, $(x_i^s,\, x_i^t)$, then firm *i* chooses output q_i that maximizes equation (3. 1), leading to the following first order conditions:

$$\frac{\partial \pi_i}{\partial q_i} = p_i' q_i + p_i - c + f(x_i) = 0, \quad \text{where} \quad i = 1, 2. \qquad (3.\ 2)$$

Suppose that $\pi_{ii} = \partial^2 \pi_i / \partial q_i^2$ and $\pi_{ij} = \partial^2 \pi_i / \partial q_i \partial q_j$. $\pi_{ii} = p_i'' q_i + 2 p_i' < 0$ by the second order conditions of profit maximization, and $\pi_{ij} = \theta(p_i'' q_i + p_i') < 0$ because of strategic substitution of outputs. Then, the stability condition is satisfied, which means that the Jacobian determinant of the profit function is positive, i.e. $J_1 = \pi_{ii}\pi_{jj} - \pi_{ij}\pi_{ji} > 0$. The two first order conditions of equation (3. 2) can be solved to draw the Cournot-Nash equilibrium outputs and profits, denoted by $q_i^*(x_i^s, x_i^t)$ and $\pi_i^*(x_i^s, x_i^t)$, $i = 1, 2$.

I now examine how changes in R&D investments affect the market outcomes. First, I look at the effect of a change in the amount of investment in idiosyncratic research x_i^s. Differentiating equation (3. 2) with respect to x_i^s gives

$$\begin{pmatrix} \pi_{ii} & \pi_{ij} \\ \pi_{ji} & \pi_{jj} \end{pmatrix} \begin{pmatrix} \partial q_i^* / \partial x_i^s \\ \partial q_j^* / \partial x_i^s \end{pmatrix} = \begin{pmatrix} -f_i' \\ -f_j' \gamma(x_j^t)\beta\varphi \end{pmatrix},$$

and solving them for $\partial q_i^* / \partial x_i^s$ and $\partial q_j^* / \partial x_i^s$, then I have the following comparative statics with a symmetric property of outcomes:

$$\frac{\partial q_i^*}{\partial x_i^s} \underset{symm}{=} \frac{1}{J_1}\left[\pi_{ij}\gamma(x^t)\beta\varphi - \pi_{jj}\right] f' > 0, \qquad (3.\ 3)$$

$$\frac{\partial q_j^*}{\partial x_i^s} \underset{symm}{=} \frac{1}{J_1}\left[\pi_{ji} - \pi_{ii}\gamma(x^t)\beta\varphi\right] f', \qquad (3.\ 4)$$

$$\frac{\partial Q^*}{\partial x_i^s} = \frac{\partial q_i^*}{\partial x_i^s} + \frac{\partial q_j^*}{\partial x_i^s} \underset{symm}{=} \frac{1}{J_1}\Big[(\pi_{ij} - \pi_{jj})(1 + \gamma(x^t)\beta\varphi)\Big] f' > 0. \qquad (3.\ 5)$$

Since the stability condition implies $\left|\pi_{jj}\right| > \left|\pi_{ij}\right|$ in the symmetric case, equation (3. 3) is always positive, so an idiosyncratic R&D increases its own output q_i^*. It means that the more research a firm conducts on its own behalf, the lower its marginal cost, leading to higher output. However, a higher output for one firm implies a decrease in the rival's output, whereas in the presence of spillovers an increase in its idiosyncratic research also reduces the rival's production cost, resulting in a higher rival's output. Its effect on the rival output q_j^* is determined by the relative magnitude of these two conflicting forces, which depends on the strength of spillovers realized by the magnitude of β, φ, and $\gamma(x^t)$.

Equation (3. 4) can be rewritten as

$$\frac{\partial q_j^*}{\partial x_i^s} \underset{symm}{=} \frac{1}{J_1}\Big[\theta(p''q + p') - (p''q + 2p')\gamma(x^t)\beta\varphi\Big] f'.$$

In the above equation, if $\gamma(x^t)\beta\varphi$ is large enough (small enough) so that the bracket above is positive (negative), then equation (3. 4) is positive (negative). Given a large spillover, the spillover effect dominates the own effect and accordingly an increase in x_i^s raises q_j^*. The presence of an absorptive capacity, however, requires a higher critical rate of exogenous spillover to derive the favorable effect of one's own research on the rival's output, because of the imperfect assimilation of the rival's externally exposed knowledge $(\gamma < 1)$. Nonetheless, the aggregate industry effect of x_i^s is not ambiguous. Since $\pi_{ij} - \pi_{jj} > 0$ in equation (3. 5), the market output Q^* always increases with an expenditure on x_i^s irrespective of whether the exogenous spillover rate and the absorptive capacity are large or small. In summary, I have

Result 1. If $(p''q+p')/(p''q+2p')<\gamma\beta\varphi/\theta$*, an increase in idiosyncratic R&D expenditure by a firm raises both its own output and its rival's output. On the other hand, if* $(p''q+p')/(p''q+2p')>\gamma\beta\varphi/\theta$*, it leads to a higher own output and a lower rival output. The industry aggregate output is always boosted by one's idiosyncratic research.*

A firm's knowledge in the public domain is no longer a free good in this model. On the part of the firm the existence of absorptive capacity implies a decrease in the rival's use of its own spilled-over knowledge. This results in decreasing its own output loss caused by the leakage of knowledge to the rival. At the same time its own absorptive capacity makes it difficult to utilize the knowledge created by the rival. The first term of equation (3. 3) and the second term of equation (3. 4) capture these effects of absorptive capacity. As a result, comparing the case of absorptive capacity $(\gamma<1)$ to the case where firms obtain the rivals' specific knowledge $(\gamma=1)$ without cost, then I obtain

$$\left(\frac{\partial q_i^*}{\partial x_i^s}\right)_{\gamma<1} > \left(\frac{\partial q_i^*}{\partial x_i^s}\right)_{\gamma=1} \quad \text{and} \quad \left(\frac{\partial q_j^*}{\partial x_i^s}\right)_{\gamma<1} < \left(\frac{\partial q_j^*}{\partial x_i^s}\right)_{\gamma=1} \qquad (3.\ 6)$$

Next, I analyze how the individual firm's output and the industry aggregate output at the second stage equilibrium react to a change in the firm's investment in absorptive capacity in the first stage. Similarly, differentiating equation (3. 2) with respect to x_i^t yields

$$\begin{pmatrix} \pi_{ii} & \pi_{ij} \\ \pi_{ji} & \pi_{jj} \end{pmatrix} \begin{pmatrix} \partial q_i^*/\partial x_i^t \\ \partial q_j^*/\partial x_i^t \end{pmatrix} = \begin{pmatrix} -f_i'\gamma'(x_i^t)\beta\varphi x_j^s \\ 0 \end{pmatrix},$$

and solving it for $\partial q_i^*/\partial x_i^t$ and $\partial q_j^*/\partial x_i^t$ and using symmetry, then I get

$$\frac{\partial q_i^*}{\partial x_i^t} \underset{symm}{=} \frac{1}{J_1}\left[-\pi_{jj}\gamma'(x^t)\beta\varphi x^s\right] f' > 0, \qquad (3.\ 7)$$

$$\frac{\partial q_j^*}{\partial x_i^t} \underset{symm}{=} \frac{1}{J_1}\left[\pi_{ji}\gamma'(x^t)\beta\varphi x^s\right] f' < 0, \tag{3. 8}$$

$$\frac{\partial Q^*}{\partial x_i^t} = \frac{\partial q_i^*}{\partial x_i^t} + \frac{\partial q_j^*}{\partial x_i^t} \underset{symm}{=} \frac{1}{J_1}\left[(\pi_{ji} - \pi_{jj})\gamma'(x^t)\beta\varphi x^s\right] f' > 0. \tag{3. 9}$$

The effects of x_i^t on outputs are quite obvious. Equations (3. 7) and (3. 8) show that increasing expenditures to enhance absorptive capacity leads to a higher own output while shrinking the rival's output. Similar to the effect of x_i^s, however, in equation (3. 9) the industry aggregate output level always increases when one of the firms increases its investment in identical research. Improving absorptive capacity directly increases own output, whereas an increase in own output indirectly affects the rival's output by depressing the market price. Unless the price change does not perfectly reflect the increase in own output, the industry aggregate output always enlarges with x_i^t.

While the spillover parameter β is fixed in this model, an actual value of β may be changeable according to the extent of the government's IPR protection. To show how the output level is changed when the government loosely or tightly enforces IPR protection, differentiating equation (3. 2) with respect to β, then

$$\pi_{ii}\frac{\partial q_i^*}{\partial \beta} + \pi_{ij}\frac{\partial q_j^*}{\partial \beta} = -f_i'\gamma(x_i^t)\varphi x_j^s.$$

With symmetry, I get

$$\frac{\partial q^*}{\partial \beta} \underset{symm}{=} -\frac{1}{(\pi_{ii} + \pi_{ij})}\left[f'\gamma(x^t)\varphi x^s\right] > 0. \tag{3.10}$$

Equation (3.10) is always positive and accordingly, if the government loosens IPR protection enforcement (higher β) in the second stage of the game, it can increase industry output.[8]

In the rest of this section I take a tractable example to provide a better understanding of second stage outcomes of the game. Suppose that the two firms face a linear demand function, which is given by

$$p_i = a - b(q_i + \theta q_j). \tag{3.11}$$

The maximization problem for firm *i* is then described as

$$\max_{q_i} \ \pi_i = [a - b(q_i + \theta q_j) - c + f(x_i)]q_i - (x_i^s + x_i^t),$$

leading to the following first order conditions:

$$\frac{\partial \pi_i}{\partial q_i} = -2bq_i - b\theta q_j + \alpha + f(x_i) = 0, \tag{3.12}$$

where $\alpha = a - c > 0$ to ensure positive outcomes. The profit function is strictly concave in quantity and the second stage solutions are stable because the second order and stability conditions are satisfied as follows:

$$\pi_{ii} = -2b < 0,\ \pi_{ij} = -b\theta < 0,\ \text{ and }\ \pi_{ii}\pi_{jj} - \pi_{ij}\pi_{ji} = b^2(4+\theta^2) > 0.$$

The optimal output follows from the first order conditions:

$$q_i^* = \frac{2(\alpha + f(x_i)) - \theta(\alpha + f(x_j))}{b(4-\theta^2)}. \tag{3.13}$$

[8] Equation (3.10) represents the impact of an increase in β on q^*, after a firm's investments in x^s and x^t are already made. However, if the level of β is revealed before the firm invests in x^s and x^t, the results can vary because a change in β affects the firm's decision on investments in x^s and x^t. This is discussed in section IV.

With symmetry the comparative statics for expenditures on x_i^s and x_i^t are presented in equations A1.1 through A1.6 of appendix 1. In equations A1.1 and A1.3 the effects of x_i^s on the own output and on the market output are always positive and the results from equations (3. 3) and (3. 5) are confirmed. As seen in equation A1.2 the direction of the effect on the rival's output is determined by the sign of the parenthesis. Comparing it to the costless case, I confirm that inequalities in (3. 6) hold and the introduction of absorptive capacity increases the critical rate of β to $\theta / 2\gamma\varphi$, which is greater than $\theta / 2\varphi$ in the costless case. As a result, I obtain

Result 1.1. When the demand function is specified by equation (3.11), the critical rate of exogenous spillovers in equation (3. 4) is given as $\theta / 2\gamma\varphi$. *An increase in idiosyncratic research by a firm leads to a higher (higher) own output and a higher (lower) rival's output if and only if* $\beta > \theta / 2\gamma\varphi$ $(\beta < \theta / 2\gamma\varphi)$.

Equations A1.4 through A1.6 present a linear demand version of the effects of investment in x_i^t. Since the positive effect of x_i^t on the own output is stronger than its negative effect on the rival output, as given in equations A1.4 and A1.5 respectively, an improvement in absorptive capacity increases the total output Q^*.

IV. FIRST STAGE (R&D STAGE)

In the first stage of the game, firm *i* simultaneously chooses its level of the two types of R&D investments x_i^s and x_i^t to maximize its own profit. Firm *i* is conscious of the dependence of output on their R&D efforts. Given the solutions to the second stage problem, the first stage profit function can be defined as

$$\pi_i^* = [p_i(q_i^* + \theta q_j^*) - c + f(x_i)]q_i^* - (x_i^s + x_i^t),\ i,\ j = 1,2 \text{ and } i \neq j \quad (4.\ 1)$$

with the associated first order conditions

$$\frac{\partial \pi_i^*}{\partial x_i^s} = \left[f_i' + p_i'\theta \frac{\partial q_j^*}{\partial x_i^s} \right] q_i^* - 1 = 0, \tag{4. 2}$$

$$\frac{\partial \pi_i^*}{\partial x_i^t} = \left[f_i'\gamma'(x_i^t)\beta\varphi x_j^s + p_i'\theta \frac{\partial q_j^*}{\partial x_i^t} \right] q_i^* - 1 = 0. \tag{4. 3}$$

Similar conditions holds for firm *j*. In equation (4. 2) the first term represents the effect that a firm's idiosyncratic research increases its profit by directly reducing its marginal cost. At the same time the firm's efforts to create firm-specific innovations reduce the rival's marginal cost through the spillover. The second term of equation (4. 2) is rewritten as $J_1^{-1} p_i'\theta(\pi_{ji} - \pi_{ii}\gamma(x_j^t)\beta\varphi) f_j'$ by equation (3. 4), and in the equation above the second term of the parenthesis catches the spillover effect of own research. I observe that the effect of its own R&D is weakened by outflows of knowledge to the rival, depending on the rival's absorptive capacity and regulatory and technological factors. Similarly, the term in the bracket of equation (4. 3) captures the positive effect of the rival's externally available idiosyncratic innovations.

These first order conditions provide useful insight into the firms' strategic behaviors associated with incentives for R&D. Similar to Qui and Tao (1998), I divide equations (4. 2) and (4. 3) into the following two parts:

$$\frac{\partial \pi_i^*}{\partial x_i^s} = \frac{\partial \pi_i}{\partial x_i^s} + \frac{\partial \pi_i}{\partial q_j} \frac{\partial q_j^*}{\partial x_i^s} \tag{4. 4}$$

$$\frac{\partial \pi_i^*}{\partial x_i^t} = \frac{\partial \pi_i}{\partial x_i^t} + \frac{\partial \pi_i}{\partial q_j} \frac{\partial q_j^*}{\partial x_i^t} \tag{4. 5}$$

As seen in equations (4. 4) and (4. 5) above, the first order derivatives of profit function with respect to the two types of research consist of the two motives, profit and strategic. In each equation, the former suggests the profit motive, which means that a firm's R&D increases its profit directly by reducing the production cost. The latter catches the strategic motive that the firm's R&D has an indirect impact on its profit through changing the rival's output.

The strategic motive for idiosyncratic research x_i^s could be either positive or negative in equation (4. 4). The sign of this term is determined by $\partial q_j^* / \partial x_i^s$, which is given by equation (3. 4). As mentioned in the previous section, when the realized spillover rate is small enough, $\partial q_j^* / \partial x_i^s$ is negative and consequently the strategic motive is positive. The first order conditions then suggest that the firm is overinvesting in its own R&D. On the other hand, if the spillover is large enough, then the firm is underinvesting in x_i^s.[9] In Spencer and Brander (1983) the absence of spillovers results in overinvesting in R&D because the strategic motive is always positive, while in this model whether firms overinvest or underinvest is uncertain and actually relies on the magnitude of γ, β, and φ. However, it is obvious that firms are likely to invest more in x_i^s in the presence of absorptive capacity $(\gamma < 1)$ when compared to the costless case $(\gamma = 1)$.

In equation (4. 5), meanwhile, firms have an incentive to overinvest in identical research x_i^t because an improvement in absorptive capacity reduces the rival's output. Since γ is increasing $(\gamma' > 0)$ and concave $(\gamma'' < 0)$ in x_i^t, a smaller x_i^t implies a bigger incentive to invest in x_i^t As γ' approaches zero, the incentive for investment in x_i^t disappears. As a consequence, together with the statements in results 1 and 1.2, I obtain

Result 2. If $(p''q + p')/(p''q + 2p') > \gamma\beta\varphi/\theta (< \gamma\beta\varphi/\theta)$, *a firm has an incentive for overinvestment (underinvestment) in idiosyncratic R&D. Considering the linear demand of equation (3.11) the critical rate of* β *is given as* $\theta / 2\gamma\varphi$. *On the other hand, a firm always has an incentive for overinvestment in identical R&D.*

9 As a result, the government's R&D subsidy for firm-specific research may be justified when the spillover is sufficiently large. A discussion of R&D policy will take place in the next section in detail.

The first order conditions of equations (4. 2) and (4. 3) also describe how firms should distribute their R&D resources between the two types of research x_i^s and x_i^t in the first stage of the game. Setting the two equations equal gives

$$\left(f_i' - f_i'\gamma'(x_i^t)\beta\varphi x_j^s \right) + p_i'\theta\left(\frac{\partial q_j^*}{\partial x_i^s} - \frac{\partial q_j^*}{\partial x_i^t} \right) = 0 \qquad (4.\ 6)$$

Since the effect of x_i^t on the rival's output is always negative, the second term of equation (4. 6) is negative if $\partial q_j^* \big/ \partial x_i^s$ is positive. It implies that the first term should be positive when the spillover of x_i^s is large enough. In other words, if $(p''q + p')/(p''q + 2p') < \gamma\beta\varphi/\theta,$ then the firms should split their R&D budget between x_i^s and x_i^t to be $f_i' > f_i'\gamma'(x_i^t)\beta\varphi x_j^s,$ which means that the marginal productivity of x_i^s is greater than that of x_i^t. As a result, with a large spillover the firms tend to allot their R&D resource to x_i^t rather than x_i^s and ultimately they are likely to underinvest in x_i^s, but overinvest in x_i^t. This result accords with the analysis in the preceding paragraph.

Equations (4. 2) and (4. 3) jointly determine the firms' optimal R&D investments and the corresponding profits. In the symmetric case, firm subscripts can be suppressed. Before solving the equations, I impose the following assumption on the profit function for the sake of guaranteeing the existence of solutions to the first stage problem:

Assumption 1. In the symmetric case the profit function is strictly concave in x^s *and* x^t, *satisfying both second order and the stability conditions, i.e.*

$$\pi_{kl}^* < 0 \ \textit{ for } \ k = l, \ \textit{ where } \ \pi_{kl}^* = \frac{\partial^2 \pi^*}{\partial x^k \partial x^l} \ \textit{ for } \ k, l = s, t \ \textit{ and } \ J_2 = \pi_{ss}^* \pi_{tt}^* - \pi_{st}^* \pi_{ts}^* > 0.$$

Together with the assumption above, equation (4. 6) yields the equilibrium amount of idiosyncratic research x^{s*}. As presented in equation (4. 7) the optimal spending on x^s is specified as a function of research injected to improve absorptive capacity and the other parameters:

$$x^{s*} = \frac{1}{\gamma' \beta \varphi} - \frac{p' \theta \pi_{ii} \gamma}{\left(p' \theta \pi_{ij} + J_1\right)\gamma'}. \tag{4. 7}$$

Partially differentiating equation (4. 7) with respect to β provides the comparative static for a change in the exogenous spillover rate at a certain level of absorptive capacity. According to De Bondt (1996), Poyago-Theotoky (1999), and Kang (2006), an increase in β lowers the equilibrium expenditure on x^s when the level of absorptive capacity is fixed. In the model of endogenous absorptive capacity, however, the impact of β on x^s are no longer determined unilaterally because a change in β affects the optimal amount of investment in absorptive capacity x^t. In consideration of this, totally differentiating equations (4. 2) and (4. 3) with respect to x_i^s, x_i^t and β, then in the symmetric case, I have

$$\begin{pmatrix} \pi_{ss}^* & \pi_{st}^* \\ \pi_{tt}^* & \pi_{ts}^* \end{pmatrix} \begin{pmatrix} \partial x^s / \partial \beta \\ \partial x^t / \partial \beta \end{pmatrix} = \begin{pmatrix} -\pi_{s\beta}^* \\ -\pi_{t\beta}^* \end{pmatrix}, \text{ where } \pi_{k\beta}^* = \partial^2 \pi^* / \partial x^k \partial \beta, \quad k = s, t,$$

leading to the following comparative statics:

$$\frac{\partial x^s}{\partial \beta} = \frac{1}{J_2}\left(\pi_{st}^* \pi_{t\beta}^* - \pi_{tt}^* \pi_{s\beta}^*\right) \text{ and } \frac{\partial x^t}{\partial \beta} = \frac{1}{J_2}\left(\pi_{st}^* \pi_{s\beta}^* - \pi_{ss}^* \pi_{t\beta}^*\right), \tag{4. 8}$$

where $\pi_{kl}^* < 0$ for $k = l$, $k, l = s, t$ and $J_2 > 0$ by assumption 1. It seems that $\pi_{st}^* < 0$ for $k \neq l$ because of strategic substitution between x^s and x^t.[10] Hence I obtain

[10] If the demand function is specified, a condition for strategic substitution can be drawn. I will draw this condition in the linear demand case later.

Result 3. When x^s *and* x^t *are strategic substitutes, i.e.* $\pi^*_{st} < 0$*, it is sufficient for* $\partial x^s / \partial \beta < 0$ *and* $\partial x^t / \partial \beta > 0$ *that* $\pi^*_{s\beta} < 0$ *and* $\pi^*_{t\beta} > 0$.

In result 3, the strategic substitution between x^s and x^t implies that an increase in x^t leads to an increase in the rival's use of own innovation x^s and consequently a decrease in productivity of x^s. The conditions for β may be very natural because an increase in β improves the return on investment in absorptive capacity while reduces profitability of investment in idiosyncratic research, due to a larger leak-out of its results to the rival.

Result 3 suggests that equation (3.10) is not valid any longer if the rate of β is revealed before the firms' decisions on x^s and x^t are made. For instance, if the government announces the level of its IPR protection in the preceding stage, the firms can respond to the change by adjusting the amounts of x^s and x^t. In this case, equation (3.10) should be changed as follows:

$$\left.\frac{\partial q^*}{\partial \beta}\right|_{symm} = -\frac{1}{(\pi_{ii} + \pi_{ij})}\left[(1+\gamma\beta\varphi)\frac{\partial x^s}{\partial \beta} + (\gamma + \gamma'\beta\frac{\partial x^t}{\partial \beta})\varphi x^s\right] f' \qquad (4.\ 9)$$

Equations (3.10) and (4. 9) imply that when the government intentionally increases the level of β by loosening IPR protection enforcement, it can boost the industry output in the short term while its long run impact is not clear. If an increase in β significantly reduces the amount of x^s so that the sign of the bracket in equation (4. 9) becomes negative, then it eventually leads to a decrease in the industry output.[11]

[11] After firms make their investments, increasing β apparently raises q^*, however, increased β also has a negative impact on firms' investment x^s in the next period, making the overall effect on q^* ambiguous. In this regard, a simulation result is presented in section VI. It shows that the effect of an increase in β on q^* is negative. For another parameter, a similar equation can be drawn. However, equation (4. 9) has a special meaning to the point that the degree of β is manageable by the government.

I now continue the example started in the previous section and derive a linear demand version of the results in this section. Using the second stage outcomes of equation (3.13), the first stage profit function becomes

$$\pi_i^* = \frac{1}{b(4-\theta^2)^2}\left[\alpha(2-\theta)+2f(x_i)-\theta f(x_j)\right]^2-(x_i^s+x_i^t), \qquad (4.10)$$

The amounts of x_i^s and x_i^t that maximize equation (4.10) can be derived from the following first order conditions:

$$\frac{\partial \pi_i^*}{\partial x_i^s} = \frac{2}{b(4-\theta^2)^2}\left[\alpha(2-\theta)+2f(x_i)-\theta f(x_j)\right]\left[2f_i'-f_j'r(x_j^t)\beta\varphi\theta\right]-1=0, \qquad (4.11)$$

$$\frac{\partial \pi_i^*}{\partial x_i^t} = \frac{2}{b(4-\theta^2)^2}\left[\alpha(2-\theta)+2f(x_i)-\theta f(x_j)\right]\left[2f_i'r'(x_i^t)\beta\varphi x_j^s\right]-1=0. \qquad (4.12)$$

It is supposed that assumption 1 is satisfied and thus the first stage profit function is strictly concave in x_i^s and x_i^t.[12] Then the symmetric solution to investment in idiosyncratic research is described as a function of x_i^t as follows:

$$x^{s*} = \frac{2-\gamma\beta\varphi\theta}{2\gamma'\beta\varphi}. \qquad (4.13)$$

Equation (4.13) represents the linear demand version of equation (4. 7). Partially differentiating it with respect to β, then

$$\frac{\partial x^{s*}}{\partial \beta} = -\frac{1}{\gamma'\beta^2\varphi} < 0 \qquad (4.14)$$

[12] In the linear demand case assumption 1 is shown in appendix 2.

Thus I confirm that an increase in the exogenous spillover rate has a negative effect on x_i^s at a certain level of absorptive capacity.

I next derive the condition for result 3 in the case of linear demand. The second order conditions require π_{ss}^* and π_{tt}^* (equations A2.1 and A2.2 in appendix 2 respectively) to be negative. For π_{ss}^* to be negative, $f'^2 + (2-\theta)(\alpha + f)f''$ should be negative because $(2-\gamma\beta\varphi\theta)^2 > 2-\gamma^2\beta^2\varphi^2\theta^2 > 2-\gamma^2\beta^2\varphi^2\theta$.

Furthermore, $2f'^2 + (2-\theta)(\alpha + f)f''$ being negative is a sufficient condition that π_{tt}^* is negative. It implies a sufficiently high curvature for the knowledge production function *f*. In other words, if $\left|f'^2 + (\alpha + f)f''\right| >$ $\left|(1/2)\theta(\alpha + f)f''\right|$, then the second order conditions are satisfied, and π_{st}^* (equation A2.3 in appendix 2) automatically has a negative sign, which means that x^s and x^t are strategic substitutes. To sum up, I have

Result 3.1. When the demand function is specified by equation (3.11), the second order conditions of the first stage profit maximization problem are satisfied, and x^s *and* x^t *are strategic substitutes if the concavity of function f is strong enough so that* $\left|f'^2 + (\alpha + f)f''\right| > \left|(1/2)\theta(\alpha + f)f''\right|$.

I now look at the second order derivatives of the profit function with respect to β, which are stated in appendix 3. It is easy to see that $\pi_{s\beta}^*$ (equation A3.1) should be negative if the second order conditions are satisfied. However, the sign of $\pi_{t\beta}^*$ is not evaluated in a simple way. An increase in the exogenous spillover rate improves productivity of investment in absorptive capacity x^t, whereas the increased total amount of effective R&D weakens the effect. Hence the sign of $\pi_{t\beta}^*$ (equations A3.2) depend on the relative magnitude of these two conflicting impacts. Finally I obtain the following condition under which the optimal expenditure on idiosyncratic research x^s (absorptive capacity x^t) decreases (increases) as the exogenous spillover parameter increases:

Result 3.2. Given Result 3.1, the comparative statics for a change in the exogenous spillover rate are given by

$$\frac{\partial x^s}{\partial \beta} < 0 \;\; and \;\; \frac{\partial x^t}{\partial \beta} > 0 \;\; if \;\; \left| f'^2 + (\alpha + f) f'' \right| < \left| \frac{1}{\gamma \beta \varphi x^s} (\alpha + f) f' \right|.$$

V. R&D SUBSIDY

In this section I examine the impact of government intervention on firms' R&D activities. Introducing the government sector extends the model into the three-stage game. I assume that the government maximizes social welfare by improving the knowledge base of its country. Suppose that the government is interested in subsidizing firms' idiosyncratic research first. Then the order of moves in the game is as follows: in the first stage, the government announces its subsidy rate s^s (tax if negative) for idiosyncratic research. Given the subsidy rate s^s, firms simultaneously decide their R&D investments and outputs in the second and third stages respectively.

In the R&D stage then firm i faces its profit function, which is given by

$$\pi_i^* = \left[p_i(q_i^* + \theta q_j^*) - c + f(x_i) \right] q_i^* - (1 - s^s) x_i^s - x_i^t, \tag{5. 1}$$

leading to the first order conditions:

$$\frac{\partial \pi_i^*}{\partial x_i^s} = \left[f_i' + p_i' \theta \frac{\partial q_j^*}{\partial x_i^s} \right] q_i^* - (1 - s^s) = 0 \tag{5. 2}$$

$$\frac{\partial \pi_i^*}{\partial x_i^t} = \left[f_i' \gamma'(x_i^t) \beta \varphi x_j^s + p_i' \theta \frac{\partial q_j^*}{\partial x_i^t} \right] q_i^* - 1 = 0 . \tag{5. 3}$$

Solving equations (5. 2) and (5. 3) simultaneously gives the equilibrium R&D investments and profits as a function of s^s i.e. $x_i^{s^*}(s^s)$, $x_i^{t^*}(s^s)$ and $\pi_i^{**}(s^s)$.

The impact of R&D subsidy on the two types of research can be obtained by totally differentiating the first order conditions with respect to x_i^s, x_i^t, and s^s. With symmetry I get

$$\begin{pmatrix} \pi_{ss}^* & \pi_{st}^* \\ \pi_{tt}^* & \pi_{ts}^* \end{pmatrix} \begin{pmatrix} \partial x^s / \partial s^s \\ \partial x^t / \partial s^s \end{pmatrix} = \begin{pmatrix} -1 \\ 0 \end{pmatrix} ,$$

and solving this equation system yields

$$\frac{\partial x^s}{\partial s^s} = -\frac{\pi_{tt}^*}{J_2} > 0 \quad \text{and} \quad \frac{\partial x^t}{\partial s^s} = \frac{\pi_{ts}^*}{J_2} . \tag{5. 4}$$

In equations (5. 4) $\partial x^s / \partial s^s$ is always positive by the second order conditions, while $\partial x^t / \partial s^s$ is negative under the condition of strategic substitutes between x_i^s and x_i^t.

In the first stage the government, meanwhile, chooses its R&D subsidy rate so as to maximize its welfare, which is defined as the profits of firms minus the subsidy payments, for simplicity,[13] i.e.

$$W^*(s^s) = \pi_i^{**}(s^s) + \pi_j^{**}(s^s) - s^s(x_i^{s^*} + x_j^{s^*}) .$$

Since $x_i^{s^*} = x_j^{s^*}$ and $\pi_i^{**}(s^s) = \pi_j^{**}(s^s)$ as a result of symmetry, the government's problem can be compressed into finding the optimal subsidy rate for idiosyncratic research that maximizes firm *i*'s profit.

[13] This definition of welfare seems not to be unusual in the context of developing countries, at least for the short term. Instead it may be simply assumed that the two firms compete in the third market. Ideally, however, the government maximizes the social welfare including the consumer surplus.

As with the other stages' optimization problems, to ensure the existence of equilibrium subsidy rate s^{s^*}, I add the following restrictions to the profit function and R&D expenditure:

Assumption 2. (1) The second order derivative of π_i^{**} *with respect to* s^s *is negative, i.e.* $\partial^2\pi_i^{**} / \partial(s^s)^2 < 0$, *and (2) the first order derivative of* $x_i^{s^*}$ *with respect to* s^s *is greater than its second order derivative in absolute terms, i.e.* $\left|\partial x_i^{s^*} / \partial s^s\right| > \left|\partial^2 x_i^{s^*} / \partial(s^s)^2\right|$.

Under this assumption, the social welfare function W^* is strictly concave in s^s, satisfying the second order condition, $\partial^2 W^* / \partial(s^s)^2 < 0$, and there exists the optimal subsidy rate s^{s^*} that maximizes W^*.[14] This would be a sufficient assumption for the second order condition for W^*. to hold, because if the second derivative of the profit function is sufficiently large by absolute value, the second order condition could hold even if assumption 2. 2. does not.

Hence I obtain the optimal subsidy rate s^{s^*} from solving the following first order condition:

$$\frac{\partial W^*}{\partial s^s} = \frac{\partial \pi_i^{**}}{\partial s^s} - x_i^{s^*} - s^s \frac{\partial x_i^{s^*}}{\partial s^s} = 0 . \qquad (5.\ 5)$$

Equation (5. 5) gives useful insight into the government's R&D policy with regard to the firms' strategic behavior. The first term on the right hand side of equation (5. 5) can be rewritten as

[14] The second derivative of W^* is given by $\partial^2 W^* / \partial(s^s)^2 = \partial^2\pi_i^{**} / \partial(s^s)^2 - 2(\partial x_i^* / \partial s^s) - s^s\left(\partial^2 x_i^* / \partial(s^s)^2\right)$. Given assumption 2, the second order condition for W^* is satisfied, as the second term is positive by equation (5. 4) and s^S is less than 1.

$$\frac{\partial \pi_i^{**}}{\partial s^s} = \frac{\partial \pi_i^*}{\partial x_i^s}\frac{\partial x_i^{s^*}}{\partial s^s} + \frac{\partial \pi_i^*}{\partial x_j^s}\frac{\partial x_j^{s^*}}{\partial s^s} + \frac{\partial \pi_i^*}{\partial x_i^t}\frac{\partial x_i^{t^*}}{\partial s^s} + \frac{\partial \pi_i^*}{\partial x_j^t}\frac{\partial x_j^{t^*}}{\partial s^s} + \frac{\partial \pi_i^*}{\partial s^s}\,. \tag{5. 6}$$

Note that the first and third terms are zero by the first order conditions of R&D stage and the last term is $x_i^{s^*}$ by the envelope theorem. Substituting equation (5. 6) into (5. 5) gives

$$s^s\frac{\partial x_i^{s^*}}{\partial s^s} = \frac{\partial \pi_i^*}{\partial x_j^s}\frac{\partial x_j^{s^*}}{\partial s^s} + \frac{\partial \pi_i^*}{\partial x_j^t}\frac{\partial x_j^{t^*}}{\partial s^s}\,. \tag{5. 7}$$

From $\pi_i^*(x_i^s, x_i^t, s^s)$, I have

$$s^s\frac{\partial x_i^{s^*}}{\partial s^s} = \left[\left(p_i'\theta\frac{\partial q_j^*}{\partial x_j^s} + f_i'\gamma\beta\varphi\right)\frac{\partial x_j^{s^*}}{\partial s^s} + \left(p_i'\theta\frac{\partial q_j^*}{\partial x_j^t}\right)\frac{\partial x_j^{t^*}}{\partial s^s}\right]q_i^*\,. \tag{5. 8}$$

Since $\partial q_j^* / \partial x_j^s > 0$ by equation (3. 3), x_j^s decreases π_i^*, implying that it reduces the price through higher q_j^*. This impact is captured by the first term of the first parenthesis of equation (5. 8). However, in the presence of R&D spillovers x_j^s also increases π_i^* indirectly through lowering firm *i*'s production cost. As seen in the second term of the first parenthesis, the strength of this effect depends on productivity of knowledge function f', absorptive capacity γ, exogenous spillover parameter β, and technological factor φ. Since $\partial q_j^* \big/ \partial x_j^t > 0$, the parenthesis of the last term catches the negative impact of higher x_j^t on π_i^* through higher q_j^*. From equations (5. 4) I find that $\partial x_j^{s^*} \big/ \partial s^s > 0$ and $\partial x_j^{t^*} \big/ \partial s^s < 0$ when x_i^s and x_i^t are strategic substitutes. As a result, it is sufficient for s^s to be positive that $p'\theta(\partial q_j^* / \partial x_j^s) + f'\gamma\beta\varphi > 0$. Using equation (3. 3), in the symmetric case this condition becomes

$$\frac{\theta(p'p''q+2p'^2)}{(1-\theta^2)p''^2q^2+(4-\theta^2)p'p''q+4p'^2}<\gamma\beta\varphi. \tag{5. 9}$$

Assuming that the government subsidizes identical research x_i^t, the versions for s^t of equations (5. 4) and (5. 8) can be obtained in the same way:

$$\frac{\partial x^t}{\partial s^t}=-\frac{\pi_{ss}^*}{J_2}>0 \text{ and } \frac{\partial x^s}{\partial s^t}=-\frac{\pi_{st}^*}{J_2}, \tag{5.10}$$

$$s^t\frac{\partial x_i^{t*}}{\partial s^t}=\left[\left(p_i'\theta\frac{\partial q_j^*}{\partial x_j^s}+f_i'\gamma\beta\varphi\right)\frac{\partial x_j^{s*}}{\partial s^t}+\left(p_i'\theta\frac{\partial q_j^*}{\partial x_j^t}\right)\frac{\partial x_j^{t*}}{\partial s^t}\right]q_i^*. \tag{5.11}$$

Since in equation (5.10) $\partial x_j^{t*}/\partial s^t>0$ and $\partial x_j^{s*}/\partial s^t<0$ when x_i^s and x_i^t are strategic substitutes, the second term of equation (5.11) is negative. Inequality (5. 9) is a sufficient condition for $s^t<0.$ Overall, I have

Result 4. When x^s *and* x^t *are strategic substitutes, i.e.* $\pi_{st}^*=\pi_{ts}^*<0,$ *the government subsidizes investments in idiosyncratic research* $(s^s>0)$ *while imposing taxes on investments in absorptive capacity* $(s^t<0)$ *if the spillover is large enough so as to satisfy inequality (5. 9).*

Result 4.1. Given Result 3.1, i.e. $\left|f'^2+(\alpha+f)f''\right|>\left|(1/2)\theta(\alpha+f)f''\right|$ *in the linear demand case, then the rate of* β *satisfying the condition of result 4 is given as* $\theta/2\gamma\varphi.$ *If* $\beta>\theta/2\gamma\varphi,$ *the government subsidizes (taxes) investments in idiosyncratic R&D (identical R&D).*[15]

[15] Note that this is only a sufficient condition so the converse need not hold. If the second terms of equations (5. 8) and (5.11) were to be very large in absolute terms, the actual spillover rate satisfying $s^{s*}>0$ and $s^{t*}<0$ should be much smaller than the rate given by inequality (5. 9). In fact, it depends on the forms of functions and the values of parameters. As an extreme case, $s^{s*}>0$ and $s^{t*}<0$ always hold for all spillover rates.

The results above suggest that the government's R&D policy is closely related to firms' strategic behavior. In the previous section I find that a large spillover offers a weaker incentive to invest in idiosyncratic research while a stronger incentive to invest in absorptive capacity. The intuition is that with a large spillover each firm tends to free ride at a small outlay on the rival's effort rather than to take a risk of large flow-out of its valuable knowledge. After all, the firms' strategic behavior comes down to underinvestment in the former, but overinvestment in the latter. In this setting the government's optimal choice should be naturally a subsidy to pull up the firms' investment in own R&D to the desirable level and a tax to remove the socially worthless portion of investment in absorptive capacity.

It is established in the traditional R&D game that firms have a strategic motive to overinvest in R&D and consequently the government taxes the firms to restrain their strategic motive. In the presence of R&D spillover the government may or may not subsidize (tax) R&D investments depending on the spillover rate, which is exogenously determined. For example, given a large spillover the only role of the government is to subsidize its firms' R&D. In this model, however, a free ride on the other's R&D is not allowed, and instead, a firm should invest in its absorptive capacity to learn from the competitor. Since the full appropriation of the rival's knowledge is not actually possible, the presence of absorptive capacity results in a higher critical rate of exogenous spillover, which gives justification for the government intervention.

VI. SIMULATION

Introducing absorptive capacity makes strategic R&D models very complicated. Unfortunately, it is hardly possible to find analytical solutions to R&D games with absorptive capacity in most cases. Instead, in this section I find numerical solutions from a simulation example and look into the impact of a change in the exogenous spillover parameter β. First of all, to run the numerical simulation, I need to set specific functional forms and parameter values. I propose the following functional forms of absorptive capacity and knowledge production:

$$\gamma(x_i^t) = \sqrt{\frac{x_i^t}{1+x_i^t}} \quad \text{and} \quad f(x_i) = \sqrt{x_i}\text{, where } \; x_i = x_i^s + \gamma(x_i^t)\beta\varphi x_j^s .$$

The functional forms of $\gamma(x_i^t)$ and $f(x_i)$ above satisfy all the conditions suggested in section II. The magnitude of $f(x_i)$ is restricted to less than c to guarantee that MC_i is positive in equation (2. 3). The linear demand function is taken, as in equation (3.11). The parameter values are chosen as a=10, b=1, and c=2.5.

An increase in product substitution θ may discourage R&D investment through lower product prices, and on the other hand it may become an incentive to overinvest in R&D relative to the social optimum at a certain level of β and φ because R&D is likely to be a greater threat to a rival's market share. Additionally, the technological aspects may affect firms' R&D activities. For instance, as the technological similarity between the firms increases, they may place more importance on investments in absorptive capacity. Therefore, I compute the symmetric equilibrium solutions to x^s and x^t at each level of β in the following four cases: (θ=0.7, φ=0.9), (θ=0.2, φ=0.9), (θ=0.7, φ=0.3), and (φ=0.2, φ=0.3).[16]

The simulation is carried out using Mathematica 7.0. The main results are stated in tables A4-1 through A4-4 of appendix 4. It is shown in the tables that $f(x_i)$<2.5 (see column 4), the second order and stability conditions hold, and x^s and x^t are strategic substitutes (see columns 8 through 10). The simulation examples satisfy the conditions discussed in results 3.1 and 3.2 (see the last three columns). As a result, I confirm that the functional forms and the parameter values are properly selected.

As consistent with the previous theoretical findings, the optimal amount of idiosyncratic research x^s decreases as the parameter β increases. Contrary to this, the optimal amount of identical research x^t increases with β. More

[16] Firms that produce similar products are likely to have a greater ability to imitate each other's innovations than firms that are in more or less different markets. In reality, however, many products that are not substitutes at all in consumption are produced with similar technologies. I consider these various market characteristics in the simulation.

importantly, I observe that the total amount of R&D investments and knowledge production *f* decrease with the parameter β in the fourth columns of the tables. It suggests that when the degree of exogenous spillovers increases, the free-rider effect overpowers the absorptive capacity effect, corresponding to Hammerschmidt (2009). Consequently, even though I introduce absorptive capacity to the model, I reach more or less the same conclusion as in the previous studies that a higher spillover results in a lower R&D investment.

The fifth columns of the tables show that a higher β leads to a lower aggregate industry output, that is to say the sign of equation (4. 9) is likely to be negative. It suggests that the government's measure to mitigate IPR protection may discourage firms from investing and eventually reduce industry production.

Finally I find evidence supporting results 4 and 4.1. As seen from the sixth columns of the tables, in the presence of absorptive capacity the optimal policy on the part of the government would be to mostly subsidize idiosyncratic research x^s and to increase its subsidy rate as the spillover becomes stronger. However, it is shown in tables A4-3 and A4-4 that a subsidy for x^s should not be a good policy in industries with higher θ or lower φ. As θ increases, the market size decreases while firms tend to invest more in their own R&D than the optimal level. A decrease in φ lowers the actual rate of spillovers. On the other hand, the seventh columns of the tables imply that the government imposes a tax on firms' investment in absorptive capacity x^t, irrespective of the spillover rates, and applies a higher tax rate when the spillover rate becomes higher. This result may be associated with the finding from result 2 that firms always have an incentive to overinvest in x^t.

VII. CONCLUDING REMARKS

In this paper I set up a model that combines the traditional strategic R&D game and the concept of absorptive capacity. A firm's effective R&D is composed of two different types of R&D investments: one that aims to produce its own innovations (idiosyncratic R&D) and another that seeks improvements in absorptive capacity (identical R&D). In the model the spillovers cannot be realized costlessly, and instead firms need to invest in absorptive capacity to utilize knowledge in the public domain. For more flexibility, I design the model using general functional forms and parameters that represent the degree of product differentiation, technological factor, and exogenous spillover.

I find that a firm's own research can increase or decrease its rival's output, depending on the realized spillover rate, while its identical research always decreases its rival's output. The impact of its research on the rival's output affects its strategic motive to invest in R&D. In general, a firm has a tendency to underinvest in idiosyncratic research, but to overinvest in absorptive capacity, especially when the products are not much substitutable in demand and the firms adopt similar technologies in production. This tendency becomes stronger as the degree of exogenous spillover becomes larger. Given high spillovers, a firm chooses to strategically free-ride on its rival's research performances rather than to exert its own efforts. Since the former effect dominates the latter effect, the total amount of R&D investments decreases with the rate of spillovers. This is socially undesirable and thus the government intervention to offset it has some rationale. The optimal policy is that the government subsidizes idiosyncratic research, whereas it taxes identical research in most cases. Additionally, a policy to increase the level of exogenous spillover, such as loosening IPR protection, can shrink industry production.

The findings may have important implications for newly industrialized or emerging countries that consider a redirection of national R&D policy and IPR regime. Since the signing of WTO TRIPS (Agreement on Trade-related Aspects of Intellectual Property Rights) in 1995, international standards of legal protection and enforcement for IPRs have continually strengthened. Nevertheless, as many developing countries are still hesitant to strengthen IPR protection due to concerns about negative economic consequences, international disputes over IPRs are on the rise. This study shows however that IPR reforms will have a positive effect on R&D spending, especially for idiosyncratic one. It is important because the possibility that strong IPR protection can encourage local innovation and creativity in developing countries has been often overlooked. As a result, the IPR reforms and idiosyncratic R&D supports will be a more effective policy mix and ultimately lead to economic benefits.[17]

[17] This should be understood as a suggestion about the desirable direction of national R&D policy. In principle the WTO does not allow R&D subsidies. See the Agreement on Subsidies and Countervailing Measures for further information. A full discussion of this issue is beyond the scope of the study.

This study may be extended to the following two directions: one is to provide empirical evidence on the roles of R&D spillovers and absorptive capacity in firms' R&D investment decisions using actual data. However, it is not straight-forward to distinguish between the two different types of R&D. This task needs to be solved, perhaps through finding some proxies for idiosyncratic and identical research activities, before reliable empirical estimation can be performed. Another is that on the theoretical side one can introduce international competition into the model. It is a more natural setting than the local spillover of knowledge, considering that many advanced technologies created in developed countries are duplicated in developing countries. Even if international R&D spillovers are allowed, the results from the two-stage game are practically not changed. The only difference is an additional assumption on the firm location, i.e. two different firms located in two different countries. However, if the game is extended to the three-stage by introducing the government sector, the problem becomes more complicated. Since each government cares only about the profit of its domestic firm, the impact of a government's policy should be different between domestic and foreign firms. It suggests that one should examine asymmetric equilibria in the second stage. These are left for future research.

APPENDIX

A1. When the demand is linear, the comparative statics for . x_i^s . and x_i^t are calculated by

$$\frac{\partial q_i^*}{\partial x_i^s} \underset{symm}{=} \frac{2-\gamma\beta\varphi\theta}{b(4-\theta^2)} f' > 0 \qquad \text{A1.1}$$

$$\frac{\partial q_j^*}{\partial x_i^s} \underset{symm}{=} \frac{(2\gamma\beta\varphi-\theta)}{b(4-\theta^2)} f' \qquad \text{A1.2}$$

$$\frac{\partial Q^*}{\partial x_i^s} = \frac{\partial q_i^*}{\partial x_i^s} + \frac{\partial q_j^*}{\partial x_i^s} \underset{symm}{=} \frac{1+\gamma\beta\varphi}{b(2+\theta)} f' > 0 \qquad \text{A1.3}$$

$$\frac{\partial q_i^*}{\partial x_i^t} \underset{symm}{=} \frac{2\gamma'\beta\varphi x^s}{b(4-\theta^2)} f' > 0 \qquad \text{A1.4}$$

$$\frac{\partial q_j^*}{\partial x_i^t} \underset{symm}{=} \frac{\gamma'\beta\varphi\theta x^s}{b(4-\theta^2)} f' < 0 \qquad \text{A1.5}$$

$$\frac{\partial Q^*}{\partial x_i^t} = \frac{\partial q_i^*}{\partial x_i^t} + \frac{\partial q_j^*}{\partial x_i^t} \underset{symm}{=} \frac{\gamma'\beta\varphi x^s}{b(2+\theta)} f' > 0 \qquad \text{A1.6}$$

A2. Given the linear demand function of equation (3.11), in the symmetric setting the second order derivatives of the profit function with respect to x_i^s and x_i^t become

$$\pi_{ss}^* \underset{symm}{=} \frac{2}{b(4-\theta^2)^2}\left[f'^2(2-\gamma\beta\varphi\theta)^2 + (2-\theta)(\alpha+f)f''(2-\gamma^2\beta^2\varphi^2\theta)\right] \qquad \text{A2.1}$$

$$\pi_{tt}^{*} \underset{symm}{=} \frac{4}{b(4-\theta^2)^2}\left[\left(2f'^2+(2-\theta)(\alpha+f)f''\right)\gamma'^2\beta\varphi x^s+(2-\theta)(\alpha+f)f'\gamma''\right]\beta\varphi x^s$$
A2.2

$$\pi_{st}^{*}(=\pi_{ts}^{*}) \underset{symm}{=} \frac{4}{b(4-\theta^2)^2}\left[f'^2(2-\gamma\beta\varphi\theta)+(2-\theta)(\alpha+f)f''\right]\gamma'\beta\varphi x^s \qquad \text{A2.3}$$

Assumption 1 implies that $\pi_{ss}^{*}<0$, $\pi_{tt}^{*}<0$, and $J_2=\pi_{ss}^{*}\pi_{tt}^{*}-\pi_{st}^{*}\pi_{ts}^{*}>0$ so that the profit function of equation (4. 1) is strictly concave in x_i^s and x_i^t.

A3. Using the linear demand function $\pi_{s\beta}^{*}$ and $\pi_{t\beta}^{*}$ are given by

$$\pi_{s\beta}^{*} \underset{symm}{=} \frac{2(2-\theta)}{b(4-\theta^2)^2}\left[\left(f'^2+(\alpha+f)f''\right)(2-\gamma\beta\varphi\theta)-(\alpha+f)f'\theta\right]\gamma\varphi x^s \qquad \text{A3.1}$$

$$\pi_{t\beta}^{*} \underset{symm}{=} \frac{4(2-\theta)}{b(4-\theta^2)^2}\left[\left(f'^2+(\alpha+f)f''\right)\gamma\beta\varphi x^s+(\alpha+f)f'\right]\gamma'\varphi x^s \qquad \text{A3.2}$$

A4. Simulation results

A4-1. Numerical solutions at $\theta=0.7$ and $\varphi=0.9$.

B	x^s	x^t	f	q	s^s	s^t	π_{ss}	π_{tt}	$\pi_{st}(\pi_{ts})$	$C1$	$C2$	$C3$
0.1	3.920	.031	1.991	3.568	-.314	-.017	-.087	-17.247	-.087	-.237	-.099	37.141
0.2	3.693	.095	1.956	3.555	-.276	-.057	-.093	-6.924	-.091	-.250	-.104	11.807
0.3	3.426	.160	1.914	3.539	-.227	-.107	-.101	-5.000	-.097	-.267	-.111	6.848
0.4	3.158	.217	1.868	3.522	-.173	-.161	-.109	-4.293	-.103	-.287	-.118	4.996
0.5	2.902	.266	1.821	3.504	-.115	-.217	-.119	-3.941	-.110	-.311	-.127	4.096
0.6	2.663	.306	1.773	3.486	-.052	-.274	-.129	-3.735	-.118	-.336	-.137	3.597
0.7	2.443	.339	1.725	3.468	.013	-.333	-.141	-3.602	-.127	-.365	-.148	3.305
0.8	2.241	.366	1.678	3.451	.081	-.393	-.152	-3.511	-.136	-.396	-.160	3.133
0.9	2.056	.389	1.632	3.433	.153	-.455	-.164	-3.447	-.146	-.431	-.173	3.039
1.0	1.887	.407	1.586	3.416	.227	-.520	-.176	-3.402	-.156	-.469	-.188	3.001

Note: $C1=f'^2+(\alpha+f)f''$, $C2=\frac{1}{2}\theta(\alpha+f)f''$, $C3=\frac{1}{\gamma\beta\varphi x^s}(\alpha+f)f'$

A4-2. Numerical solutions at $\theta = 0.2$ and $\varphi = 0.9$.

β	x^s	x^t	f	q	s^s	s^t	π_{ss}	π_{tt}	$\pi_{st}(\pi_{ts})$	C1	C2	C3
0.1	4.947	.047	2.229	4.422	-.079	-.002	-.075	-11.966	-.075	-.169	-.022	22.091
0.2	4.841	.141	2.215	4.416	-.033	-.066	-.077	-5.351	-.076	-.173	-.022	6.851
0.3	4.712	.238	2.197	4.408	.026	-.124	-.079	-4.094	-.078	-.177	-.023	3.786
0.4	4.574	.328	2.178	4.399	.091	-.187	-.081	-3.602	-.080	-.181	-.023	2.599
0.5	4.435	.409	2.159	4.390	.160	-.254	-.084	-3.335	-.081	-.186	-.024	1.992
0.6	4.296	.482	2.138	4.381	.232	-.323	-.086	-3.162	-.083	-.192	-.025	1.631
0.7	4.159	.547	2.118	4.372	.307	-.394	-.088	-3.037	-.085	-.197	-.025	1.395
0.8	4.025	.607	2.097	4.362	.383	-.468	-.091	-2.942	-.088	-.203	-.026	1.230
0.9	3.894	.661	2.076	4.353	.462	-.544	-.093	-2.866	-.090	-.210	-.027	1.110
1.0	3.767	.710	2.055	4.343	.543	-.623	-.095	-2.803	-.092	-.216	-.028	1.019

Note: $C1 = f'^2 + (\alpha + f)f''$, $C2 = \frac{1}{2}\theta(\alpha + f)f''$, $C3 = \frac{1}{\gamma\beta\varphi x^s}(\alpha + f)f'$

A4-3. Numerical solutions at $\theta = 0.7$ and $\varphi = 0.3$.

β	x^s	x^t	f	q	s^s	s^t	π_{ss}	π_{tt}	$\pi_{st}(\pi_{ts})$	C1	C2	C3
0.1	3.996	.004	2.000	3.572	-.328	-.002	-.086	-117.345	-.086	-.234	-.098	275.348
0.2	3.927	.016	1.987	3.567	-.323	-.009	-.088	-32.287	-.088	-.239	-.100	73.182
0.3	3.826	.033	1.967	3.559	-.315	-.019	-.091	-16.618	-.090	-.246	-.103	35.585
0.4	3.704	.052	1.943	3.550	-.305	-.031	-.095	-11.166	-.094	-.256	-.106	22.293
0.5	3.571	.072	1.916	3.540	-.294	-.045	-.099	-8.652	-.097	-.266	-.110	16.044
0.6	3.435	.092	1.888	3.529	-.281	-.061	-.104	-7.288	-.102	-.279	-.115	12.582
0.7	3.298	.111	1.859	3.519	-.267	-.078	-.110	-6.465	-.107	-.292	-.120	10.449
0.8	3.164	.129	1.830	3.508	-.253	-.095	-.116	-5.931	-.112	-.306	-.126	9.035
0.9	3.034	.145	1.802	3.497	-.237	-.113	-.122	-5.565	-.117	-.321	-.131	8.048
1.0	2.909	.160	1.773	3.486	-.221	-.132	-.128	-5.304	-.122	-.336	-.137	7.330

Note: $C1 = f'^2 + (\alpha + f)f''$, $C2 = \frac{1}{2}\theta(\alpha + f)f''$, $C3 = \frac{1}{\gamma\beta\varphi x^s}(\alpha + f)f'$

A4-4. Numerical solutions at $\theta = 0.2$ and $\varphi = 0.3$.

β	x^s	x^t	f	q	s^s	s^t	π_{ss}	π_{tt}	$\pi_{st}(\pi_{ts})$	$C1$	$C2$	$C3$
0.1	4.983	.007	2.233	4.424	-.097	-.003	-.075	-76.340	-.075	-.168	-.022	163.319
0.2	4.950	.025	2.227	4.421	-.090	-.010	-.075	-21.344	-.075	-.170	-.022	42.930
0.3	4.901	.051	2.219	4.418	-.078	-.022	-.076	-11.268	-.076	-.172	-.022	20.502
0.4	4.841	.081	2.208	4.413	-.063	-.036	-.078	-7.782	-.077	-.174	-.023	12.542
0.5	4.774	.114	2.196	4.407	-.047	-.053	-.079	-6.178	-.078	-.177	-.023	8.776
0.6	4.702	.146	2.184	4.402	-.028	-.071	-.080	-5.305	-.080	-.180	-.023	6.672
0.7	4.627	.178	2.170	4.396	-.009	-.091	-.082	-4.773	-.081	-.183	-.024	5.363
0.8	4.551	.209	2.157	4.389	.012	-.112	-.084	-4.422	-.082	-.187	-.024	4.483
0.9	4.474	.239	2.143	4.383	.033	-.133	-.085	-4.175	-.084	-.191	-.025	3.859
1.0	4.397	.267	2.128	4.377	.056	-.155	-.087	-3.993	-.086	-.194	-.025	3.396

Note: $C1 = f'^2 + (\alpha + f) f''$, $C2 = \frac{1}{2}\theta(\alpha + f) f''$, $C3 = \frac{1}{\gamma\beta\varphi x^s}(\alpha + f) f'$

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