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Abstract

We study vertically related industries where both upstream and downstream producers conduct cost-reducing R&D. We find that R&D investments at the two levels of the market are strategic complements: R&D by firms at one level benefit all firms at the other level. Furthermore, R&D by a downstream firm increases the demand for the intermediate good, thereby raising the input price for rival firms. Consequently downstream firms may invest more in R&D with increased downstream competition, a possibility that never arises in a purely horizontal set-up. Increased competition in the upstream (downstream) market leads to more R&D investment by all downstream (upstream) firms. By internalizing the positive externalities between the two levels of the market, as well as the negative externalities among firms on the same level, R&D cooperation may either promote or hinder innovation, depending on the number of firms. Policy analysis based on purely horizontal R&D models may not accurately reflect the true social benefits and costs of R&D cooperation.

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I. INTRODUCTION

How market structures affects incentives for innovation is an old question in economics. Schumpeter (1942), for example, argued that large firms tend to invest more in innovation. Arrow (1962) showed that a perfectly competitive firm has a higher incentive for R&D than a monopolist. There is by now a huge body of literature dealing with various aspects of innovative R&D (see Reinganum (1989) for a survey), most of it focusing on horizontal R&D in industries where firms are competitors on the same product market. But virtually no attention has be given to R&D among vertically related industries. There is ample evidence that much R&D activity, either cooperative or otherwise, is carried out by firms that are in supplier-buyer relationships. Many service industries are important customers of machinery, electrical and transportation equipment as well as professional and scientific instruments manufacturers, and use their extensive participation in joint research ventures to induce suppliers to tailor their technological innovations to the needs of their customers (Vonortas 1997). Vonortas and Jang's (1997) detailed study of the composition of research joint ventures in the US between 1985-1995 confirms that vertical cooperation forms the most dominant type of linkage among member firms.

Our paper is among the first to study some of the issues underlying R&D in vertically related industries. We construct a simple model where upstream firms supply a homogeneous intermediate good to downstream firms who then transform it into a homogeneous final product. The downstream firms set quantities taking the input price as given. These quantities determine the derived demand for the intermediate good. Quantity-setting by the upstream producers then determines the price of the intermediate good. Firms at each level can conduct cost-reducing R&D prior to their interaction in the product market. There are no R&D spillovers.

We identify several interesting aspects of R&D incentives in this simple model. First,
research investments at the two levels of the market are strategic complements: an increase in an upstream (downstream) firm's R&D induces all downstream (upstream) firms to invest more in reducing their costs. Second, R&D by a downstream producer increases the demand for the intermediate good, thereby raising the input price its rival firms will pay. Because of this strategic effect, downstream firms may invest more in R&D with increased downstream competition, a possibility that never arises in a purely horizontal set-up. Third, the degree of competition at one level affects the R&D incentives of firms in both tiers of the market: increased competition in the upstream (downstream) market causes all downstream (upstream) firms to increase their R&D investments. Finally, we consider cooperative R&D within the same vertical set-up. Cooperative R&D internalizes two types of externalities: the negative externality in R&D investments among rival firms and the positive externality between the two tiers of the market. Depending on the degree of concentration in each tier of the market, it can either promote or hamper innovation at each level. We analyze the welfare consequences of cooperative versus competitive R&D and also consider the case of R&D cooperation at just one level of the market ('semi-cooperation').

Our analysis can be useful in formulating better government R&D policy. Since previous studies have generally considered horizontal R&D settings only, their policy implications may not capture the entire picture. For instance, we have shown that cooperative research at one level of the market affects the other tier as well. Since R&D in these two tiers are complementary, cooperation could either reduce or raise the R&D investment level in the other tier depending on whether it decreases or increases R&D in the first tier. Thus, policy analysis confined to only one tier of the market may underestimate either the social costs of R&D cooperation (when it hampers R&D in that tier) or its social benefits (when it promotes R&D in that tier).\(^1\) A more accurate cost-benefit analysis can

\(^1\) We do not model spillovers among competitors in this model. However, our analysis
be obtained within a vertical framework that captures the interaction of R&D decisions at both levels of the market. Similarly, the evaluation of the impact of government R&D subsidies even under competitive R&D is affected by the vertical interlinkage between the upstream and downstream markets.

The paper is arranged as follows. We consider competitive R&D in the next section and present the special cases of a successive monopoly and upstream monopoly/downstream duopoly to arrive at some basic insights about noncooperative R&D in this bi-level setting. We conclude this section by considering the general case of \( m \) upstream suppliers and \( n \) downstream producers. Section III considers cooperative R&D across both levels, compares the welfare consequences of cooperation with competition, and looks at the issues of side payments and semi-cooperation. Section IV concludes.

II. COMPETITIVE R&D

II.1. The Case of Successive Monopoly

We first consider the case where there is one upstream firm, \( U \), and one downstream firm, \( D \). The upstream firm supplies an intermediate good to the downstream firm which then transforms the input into a final product. There are constant returns to scale in the production of both goods, and the final good is produced with a fixed-coefficient technology (one unit of final product requiring exactly one unit of the input). Let \( c_I \) be the marginal cost of the intermediate good, \( c_F \) the marginal cost of transforming the intermediate good into the final good, \( p_I \) the price of the intermediate good, and \( p \) the price of the final good. Thus, the marginal cost of producing the final good for the downstream firm is \( p_I + c_F \). Before they interact in their respective product markets, the upstream and the downstream firms first engage in cost-reducing R&D activities. The cost of reducing the spillovers will go through in a model with such spillovers where, as is well known, horizontal R&D cooperation may either increase or decrease R&D investment, depending on the magnitudes of spillover.

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upstream firm’s marginal cost of production by \( x \) is \( \beta x^2 \) (\( \beta > 0 \)); similarly, the cost of reducing the downstream firm’s marginal cost by \( y \) is \( \gamma y^2 \) (\( \gamma > 0 \)). R&D decisions are made simultaneously and independently. Once their R&D projects are completed, firm \( D \) purchases the intermediate input from firm \( U \) at price \( p_I \) and then produces and sells the final product to consumers. The inverse demand for the final good \( Q \) is assumed to be linear: \( p = a - Q \).

Given its marginal cost of production of \( p_I + c_T - y \), the downstream firm simply charges a monopoly price \( p = (a + p_I + c_T - y)/2 \) and produces the output \( Q = (a - p_I - c_T + y)/2 \), which is also its demand for the input. Given this derived demand for the intermediate good, the upstream firm sets the input price at \( p_I = (a + c_I - x - c_T + y)/2 \). The profits of firms \( U \) and \( D \) are respectively,

\[
\pi^U = (p_I - c_I + x)Q = \frac{(a - c_I - c_T + x + y)^2}{8},
\]

\[
\pi^D = (p - p_I - c_T + y)Q = \frac{(a - c_I - c_T + x + y)^2}{16}.
\]

Note that both the quantity \( Q \) of the final good and the price \( p_I \) of the intermediate input increase with \( y \), the amount of cost-reducing R&D that firm \( D \) chooses to conduct. The intuition for this is that as it reduces its cost of production and thus increases the output of the final good, firm \( D \) essentially raises its demand for the intermediate good. At the higher demand, the upstream firm is able to sell more of the input at a higher price. Due to this positive externality, the upstream supplier benefits from the downstream firm’s R&D. This, of course, tends to dampen firm \( D \)'s incentive to innovate: note that the equilibrium overall marginal cost of production for the downstream firm is \( p_I + (c_T - y) = (a + c_I - x + c_T - y)/2 \), i.e., for each dollar increase in R&D expenditure \( y \), firm \( D \)'s overall marginal cost decreases by only half a dollar after firm \( U \) raises the input price.

In the R&D stage, firm \( U \) maximizes \( \pi^U - \beta x^2 \) over \( x \), while firm \( D \) maximizes \( \pi^D - \gamma y^2 \) over \( y \). These yield the following R&D best-response functions for firms \( U \) and
\[ x = \frac{a - c_I - c_T + y}{8\beta - 1} \quad \text{and} \quad y = \frac{a - c_I - c_T + x}{16\gamma - 1}. \]

Clearly, the R&D decisions of the upstream and the downstream firms are strategic complements: each firm will increase its R&D investment if the other firm does too. Solving for \( x \) and \( y \), we get the equilibrium investment levels,

\[ x^* = \frac{2\gamma(a - c_I - c_T)}{16\gamma\beta - 2\gamma - \beta} \quad \text{and} \quad y^* = \frac{\beta(a - c_I - c_T)}{16\gamma\beta - 2\gamma - \beta}. \]

II.2 The Case of Downstream Duopoly

Now suppose there are two downstream firms, \( D_1 \) and \( D_2 \), each like the single downstream firm in the previous section. They purchase the input from the upstream monopolist \( U \) and compete in the downstream market in quantities. Given the amounts of their R&D, \( y_1 \) and \( y_2 \), and the price \( p_I \) charged by the upstream firm, the downstream Cournot quantities are

\[ q_j = \frac{a - c_T - p_I + 2y_j - y_k}{3} \]

for \( j, k = 1, 2, j \neq k \). The derived demand for the input is then \( Q = q_1 + q_2 = [2(a - c_T - p_I) + y_1 + y_2]/3 \). Solving for the monopoly price and output for the upstream firm, we get

\[ p_I = \frac{2(a - c_T + c_I - x) + y_1 + y_2}{4} \quad \text{and} \quad Q = \frac{2(a - c_T - c_I + x) + y_1 + y_2}{8}. \]

Note that \( p_I \) is an increasing function of both downstream firms' R&D efforts. As a downstream firm, say \( D_1 \), invests in cost-reducing R&D, its market share in the final product market will expand, raising the demand for the intermediate good. This not only benefits the upstream firm because it causes the input price to rise, it also raises the rival firm's marginal cost of production for the same reason. Therefore, \( D_1 \)'s R&D imposes a positive externality on \( U \) and a negative externality on its rival \( D_2 \). In other words, a
downstream firm’s R&D confers a competitive advantage through two channels: it reduces its own marginal cost, while raising its rival’s cost, an effect that is absent in a model with horizontal R&D alone. Because of this, downstream competition provides a stronger incentive for downstream R&D. This can be seen from the marginal cost of production for a downstream firm $D_j$, given by

$$p_I + (c_T - y_j) = \frac{2(a + c_T + c_I - x) - 3y_j + y_k}{4},$$

which shows that a dollar reduction in a downstream firm’s marginal cost of transforming the intermediate good into the final product leads to a 75 cents reduction in its overall marginal cost, as compared to a 50 cents reduction in the case of downstream monopoly.

Each downstream firm’s profit is $\pi_j^D = \frac{1}{36} \left[ a - c_I + x - c_T + \frac{7}{2}y_j - \frac{5}{2}y_k \right]^2$. Its optimal amount of R&D is found by maximizing $\pi_j^D - \gamma y_j^2$. The first order condition yields the R&D best-response function

$$y_j = \frac{a - c_I + x - c_T - \frac{5}{2}y_k}{\frac{72}{7} - \frac{7}{2}}.$$

Thus, the R&D choices of the two downstream firms are strategic substitutes, while the R&D choice between a downstream firm and the upstream firm are strategic complements.

The upstream firm’s profit is given by $\pi^U = \frac{1}{6} \left[ a - c_I - c_T - x + (y_1 + y_2)/2 \right]^2$. Its R&D problem is to maximize $\pi^U - \beta x^2$. Solving for $U$’s best-response function, we get

$$x = \frac{a - c_I - c_T + (y_1 + y_2)/2}{6\beta - 1}.$$

Then the symmetric R&D equilibrium (where $y_1 = y_2 = y^*$) is

$$x^* = \frac{a - c_I - c_T}{6\beta - \frac{7}{12}\frac{\beta}{\gamma} - 1} \quad \text{and} \quad y^* = \frac{a - c_I - c_T}{\frac{72}{7} - \frac{12}{7}\frac{\gamma}{\beta} - 1}.$$

$^2$ Stability of the equilibrium requires $\beta > 1/3$ and $\gamma > 7/36$. 

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It is easily verified that both are greater than their counterparts in the case of downstream monopoly (under the stability condition). The reason that the downstream firms each invest more in R&D than in the case of a single downstream firm is precisely because of the effect of raising the rival’s cost. As the downstream firms invest more, the upstream firm increases its R&D effort as well.

II.3 The Case of $m$ Upstream Firms and $n$ Downstream Firms

Consider the general case with $m \geq 1$ upstream firms, indexed by $U_i$, and $n \geq 1$ downstream firms, indexed by $D_j$. The demand for the final good is still linear with $p = a - Q$, where $Q = \sum q_j$. Before the firms interact in the product markets, both the upstream and the downstream firms engage in cost-reducing R&D activities, where the cost of reducing $U_i$’s marginal cost of production by $x_i$ is $\beta x_i^2$ and the cost of reducing $D_j$’s marginal cost by $y_j$ is $\gamma y_j^2$. R&D decisions are made simultaneously and independently. Given their R&D decisions, and the price of the input, the downstream firms compete in Cournot fashion, resulting in an output level of

$$q_j = \frac{a - c_T - p_T + ny_j - \sum_{k \neq j} y_k}{n + 1} \quad (1)$$

for any $j, k = 1, 2, \ldots, n, j \neq k$. The derived demand for the input is thus

$$Q = \sum q_j = \frac{n(a - c_T - p_T) + \sum y_j}{n + 1},$$

or equivalently,

$$p_T = a - c_T + \frac{1}{n} \sum y_j - \frac{n + 1}{n} Q.$$  

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3 See Salinger (1988) and Ordover, Saloner and Salop (1990) for a discussion of the strategy of raising rivals' costs in models of vertical foreclosure.

4 We suppress the limits underlying any summation with the understanding that the summation ranges from 1 to $m$ (resp. $n$) if the variable pertains to the upstream (resp. downstream) firms.
The upstream firms choose quantities \( \{q_i\}_{i=1}^m \) in a Cournot game with respect to this derived demand for the intermediate good such that \( \sum q_i = Q \). This yields the Cournot equilibrium price

\[
p_I = \frac{a - c_T + \sum y_j / n + \sum (c_I - x_i)}{m + 1}
\]  
\[
(2)
\]

and the Cournot profits for each upstream firm

\[
\pi_I = \frac{n}{n + 1} \cdot \frac{\left[ a - c_T - c_I + \sum y_j / n + (m + 1)x_i - \sum_{k \neq i} x_k \right]^2}{(m + 1)^2}.
\]  
\[
(3)
\]

It is useful to note that firm \( D_j \)'s overall marginal cost is

\[
p_I + c_T - y_j = \frac{a + m c_T + \sum y_k / n - (m + 1)y_j + \sum (c_I - x_i)}{m + 1},
\]

implying that

\[
\frac{\partial (p_I + c_T - y_j)}{\partial y_j} = -\frac{(m + 1)n - 1}{(m + 1)n} \quad \text{and} \quad \frac{\partial (p_I + c_T - y_j)}{\partial y_k} = \frac{1}{(m + 1)n} \quad \text{for} \ k \neq j,
\]

a result summarized in the lemma below.

**Lemma 1.** A unit reduction in firm \( D_j \)'s marginal transformation cost decreases its overall marginal cost by \( \frac{(m + 1)n - 1}{(m + 1)n} \) and raises each rival firm's overall marginal cost by \( \frac{1}{(m + 1)n} \).

As \( n \) (or \( m \)) rises, each individual downstream firm becomes smaller relative to the industry (its Cournot output declines). So a drop in its unit cost will not shift the demand for the input as much. Thus, the increase in the input price \( p_I \) is small and hence the downstream firm gains more from each dollar of reduction in its marginal transformation cost, enhancing its incentive to innovate. For the same reason, the negative externality a downstream firm’s R&D imposes on each rival firm also diminishes, as stated in the second part of the lemma.
Substituting for \( p_I \) from equation (2) into equation (1), we get the downstream Cournot quantities

\[
q_j = \frac{1}{(m+1)(n+1)} \left[ m(a - c_I - c_T) + (m+1) \left\{ (n+1)y_j - \sum_{k \neq j} y_k \right\} - \sum y_k / n + \sum x_i \right]
\]

and profits

\[
\pi^D_j = \left[ a - \sum q_j - (p_I + c_T - y_j) \right] q_j
= \frac{\left[ m(a - c_I - c_T) + (m+1) \left\{ (n+1)y_j - \sum y_k \right\} - \sum y_k / n + \sum x_i \right]^2}{(m+1)^2(n+1)^2}.
\]  

(4)

As in the previous sections, both the upstream and downstream firms make their cost-reducing R&D decisions simultaneously and independently. In particular, an upstream firm \( U_i \) chooses \( x_i \) to maximize \( \pi_i^U - \beta x_i^2 \) (gross profits as given by equation (3) less research cost). Similarly, each downstream firm chooses \( y_j \) to maximize \( \pi^D_j - \gamma y_j^2 \) (gross profits as given by equation (4) less research cost). Focusing on the symmetric case where \( x_i = x \) and \( y_j = y \), we obtain the following best-response functions:

\[
x = \frac{a - c_I - c_T + y}{G(m,n) - 1} \quad \text{and} \quad y = \frac{a - c_I - c_T + x}{H(m,n) - 1},
\]

where

\[
G(m,n) = \frac{\beta(m+1)^2(n+1)}{mn} \quad \text{and} \quad H(m,n) = \frac{\gamma(m+1)^2(n+1)^2 n}{m[n^2(m+1) - 1]}.
\]

These two best-response functions give us the following equilibrium R&D levels:

\[
x^*(m,n) = \frac{a - c_I - c_T}{G(m,n) - G(m,n)/H(m,n) - 1}
\]  

(5)

and

\[
y^*(m,n) = \frac{a - c_I - c_T}{H(m,n) - H(m,n)/G(m,n) - 1}.
\]  

(6)
How the equilibrium R&D levels vary with the degree of competition in both the upstream and the downstream market is explored in the following proposition.

**Proposition 1.** If \( \beta \geq 1 \) and \( \gamma \geq 1 \), then

(i) \( x^* \) decreases in \( m \) for all \( n \);
(ii) \( nx^* \) increases in \( m \) for all \( n \);
(iii) \( y^* \) decreases in \( n \) for all \( n \geq 2 \) and all \( m \); \( y^*(m, 1) < y^*(m, 2) \) iff \( m < 8 \);
(iv) \( ny^* \) increases in \( n \) for all \( m \); and
(v) \( x^* \) increases in \( n \), and \( y^* \) increases in \( m \).

Proposition 1 informs us how the market structure at each level of the industry affects the incentive to innovate. As the number of upstream firms, \( m \), rises, the input market is less profitable for each \( U \) firm and consequently \( x^* \) declines (part (i)). The upstream industry as a whole invests more as competition intensifies (part (ii)). Part (v) of the proposition tells us that as one level of the industry (upstream or downstream) becomes more competitive, firms at the other level have the incentive to invest more in R&D. Upstream R&D increases with \( n \) because as the downstream market becomes more competitive, the standard double-marginalization effect is smaller and hence upstream profits go up, inducing them to invest more in R&D. As \( m \) increases, the input market becomes more competitive and contributes to the greater profitability of the downstream producers, causing the latter to increase their R&D as well.

To understand part (iii) of the proposition, recall Lemma 1 which states that as \( n \) increases, the input price becomes less responsive to a downstream producer's R&D. So each unit of a downstream firm's R&D investment leads to a larger percentage reduction in its overall marginal cost. This means that greater downstream competition tends to raise \( x^* \). But at the same time, greater competition erodes the profit in the product market which makes R&D less rewarding. Part (iii) of the proposition states that if there is a
monopoly in the downstream market (so the incentive to raise rivals' costs is absent) and a small number of upstream firms (fewer than 8), it is possible that with the entry of another downstream firm the first effect is stronger than the second, so \( y^* \) increases.\(^5\) But with two or more firms in the downstream market, the second effect dominates with any further entry, so a downstream firm invests less in R&D as \( n \) increases. Nevertheless, total downstream R&D, \( n y^* \), always increases as the degree of competition increases (part (iv)).

III. COOPERATIVE R&D

III.1 Overall R&D Cooperation

Suppose that all firms, both upstream and downstream, cooperate in choosing their R&D levels. Assuming symmetry for all the upstream firms \( (x_i = x) \) and for all the downstream firms \( (y_j = y) \) and substituting these into equations (3) and (4), we have

\[
\pi_i^U = \frac{n(a - c_T - c_I + x + y)^2}{(m + 1)^2(n + 1)}
\]  

(7)

and

\[
\pi_j^D = \frac{m^2(a - c_T - c_I + x + y)^2}{(m + 1)^2(n + 1)^2}
\]

(8)

Overall cooperation (with no cost-sharing) entails maximizing

\[
m(\pi_i^U - \beta x^2) + n(\pi_j^D - \gamma y^2) = \frac{mn(n + 1)(a - c_T - c_I + x + y)^2}{(m + 1)^2(n + 1)^2} - m\beta x^2 - n\gamma y^2.
\]

From the first order conditions we obtain the cooperative solution:

\[
x^C(m, n) = \frac{a - c_T - c_I}{\beta(m + 1)^2(n + 1)^2} - \frac{m\beta}{n(n + 1)} - 1
\]

(9)

\[
y^C(m, n) = \frac{a - c_T - c_I}{\gamma(m + 1)^2(n + 1)^2} - \frac{n\gamma}{m(m + 1)} - 1
\]

(10)

\(^5\) The cut-off point of 8 firms is probably a result of the linear demand assumed in this model.
The following proposition tells us that overall cooperation may promote or hamper innovation relative to non-cooperation in this model depending on the number of firms.

**Proposition 2.** Assume that $\beta \geq 1$ and $\gamma \geq 1$. Then,

(i) $x^C(m, n) > x^*(m, n)$ iff $m \leq 2$ and $n = 1$ or $m = 1$ and $n \geq 1$; and

(ii) $y^C(m, n) > y^*(m, n)$ iff $m = 1$ and $n \leq 2$ or $m \geq 2$ and $n = 1$.

These results are easily understood by noting that overall cooperation has two effects. First, it internalizes the negative externalities among rival firms’ R&D decisions at each level of the vertically related market tiers. This horizontal aspect of R&D cooperation tends to decrease R&D, as is well-known in the literature. Second, cooperation also internalizes the positive externalities between the two tiers of the market by taking into account the benefits of an upstream (downstream) firm’s R&D on all the downstream (upstream) firms. This vertical aspect of cooperation tends to increase R&D. So, a priori it is not clear whether overall cooperation promotes or hinders innovation.

Consider the case of upstream monopoly ($m = 1$). In this case, there is no negative externality to internalize in the upstream industry; R&D by the upstream firm benefits all the other firms in the industry. As a result, cooperation always increases upstream R&D so that $x^C(1, n) > x^*(1, n)$ for all $n$. This is so despite the fact that upstream and downstream R&D are strategic complements and that cooperation may decrease downstream R&D. But due to the horizontal aspect of R&D in the downstream market, cooperation may increase or decrease downstream R&D, depending on the number of downstream competitors. In particular, $y^C(1, n) < y^*(1, n)$ for $n \geq 3$. But if $n \leq 2$, the downstream firms invest more in R&D under cooperation despite the negative externalities between them because the vertical aspect of R&D cooperation dominates: in maximizing joint profits, the downstream firms are required to increase their R&D investments.\(^6\) Or to put it differently, as the

\(^6\) It is interesting to compare this finding with the case where cooperation occurs only
upstream R&D goes up, each downstream firm ends up investing more in R&D under cooperation.

A similar reasoning can be invoked in the case of downstream monopoly \((n = 1)\). First, R&D cooperation always increases downstream R&D activity for all \(m\) because of the vertical aspect of R&D. For \(m \geq 3\), the upstream firms each invest less in R&D under cooperation due to the negative externality arising from the horizontal R&D among them. However, they invest more in R&D when \(m \leq 2\), for in this case the negative externality between the upstream duopolists is weaker than the positive externality between them and the downstream producer.

Finally, for \(m \geq 2\) and \(n \geq 2\), Proposition 2 informs us that overall cooperation always reduces R&D at each level of the industry. This is so because in this case there are negative externalities to internalize in both tiers of the industry so that the horizontal aspect of R&D cooperation dominates the vertical aspect.

III.2. Social Welfare

R&D cooperation may or may not promote innovation depending on the degree of concentration of the downstream and upstream industries. In this subsection, we analyze the welfare effects of R&D cooperation in our model.

Given \(m\), \(n\), and R&D levels \(x\) and \(y\), the social welfare \(W(m, n)\) is given by the sum of producer and consumer surpluses less cost of R&D on both tiers of the market:

\[
W(m, n) = mx_i^U + nx_j^D + 0.5(nq_j)^2 - mx - ny,
\]

between the downstream duopolists. As the literature on pure horizontal R&D suggests, joint profit maximization by the two downstream duopolists will reduce the equilibrium R&D level. (This is also confirmed by the analysis of semi-cooperation in Section III.3.) But if the firms invite the upstream producer to participate in a joint R&D program, they will invest more in R&D relative to the case of competition since now they have to take the upstream firm's wellbeing into account.
where the third term is the consumer surplus when each downstream firm produces the Cournot output
\[ q_j = \frac{mn}{(m+1)(n+1)}(a - c_l - c_T + x + y), \]
where \(x\) and \(y\) take their respective values under coopertion or competition.

We have run simulations by substituting the equilibrium R&D and output levels corresponding to competition and cooperation into the above expression for welfare and for parameter values \(a - c_l - c_T = 10\) and \( \beta = \gamma = 1\). These are presented in Tables 1 and 2.

(Insert Tables 1 and 2 here)

Cooperation in R&D certainly increases all firms’ aggregate profits, i.e., the producers’ surplus is uniformly higher. In the case of upstream or downstream monopoly (either when \(m = 1\) or when \(n = 1\)), cooperation may lead to higher equilibrium R&D levels (Proposition 2), which translates into a lower price for the final product. Consequently consumer surplus is larger under cooperation and social welfare is also higher than under competition. However, for two or more upstream or downstream firms, R&D cooperation hinders innovation sufficiently so that consumers suffer from the resulting higher price. The consumer surplus is reduced so much that it is not sufficiently compensated by the increase in producer surplus, resulting in lowered social welfare.

III.3 R&D Cooperation and Side-payments

Cooperation of course increases aggregate industry profits. However, since the firms are not symmetric, they may not benefit from cooperation equally. It may even be the case that a firm’s profit under cooperation is lower than that under competition if the firm is “asked” by its partners to increase its R&D investments drastically. This section makes the point that in a vertical industry, R&D cooperation may entail side payments by upstream firms to compensate downstream firms for their R&D contributions. We illustrate this in special case of successive monopoly.
Consider the case with one upstream firm \((m = 1)\) and one downstream firm \((n = 1)\) and the R&D cost parameters \(\beta = \gamma = 1\). Given the parameter values, we have
\[
x^C = y^C = \frac{3(a - c_I - c_T)}{10}
\]
and
\[
x^* = \frac{8(a - c_I - c_T)}{105} \quad \text{and} \quad y^* = \frac{16(a - c_I - c_T)}{105}.
\]
From these, we can calculate firms' profits to be
\[
\pi_i^U(x^C, y^C) = \frac{(a - c_I - c_T + x^C + y^C)^2}{8} - (x^C)^2 = 0.23(a - c_I - c_T)^2
\]
\[
\pi_j^D(x^C, y^C) = \frac{(a - c_I - c_T + x^C + y^C)^2}{16} - (y^C)^2 = 0.07(a - c_I - c_T)^2
\]
under cooperation and
\[
\pi_i^U(x^*, y^*) = \frac{(a - c_I - c_T + x^* + y^*)^2}{8} - (x^*)^2 = 0.1655(a - c_I - c_T)^2
\]
\[
\pi_j^D(x^*, y^*) = \frac{(a - c_I - c_T + x^* + y^*)^2}{16} - (y^*)^2 = 0.0885(a - c_I - c_T)^2
\]
under competition, respectively. Since \(0.07 < 0.0885\), R&D cooperation reduces the downstream firm's profits, although it increases joint profits in the industry.

Whether this incentive problem arises or not depends not only on the number of firms but also the relative cost of research (the values of \(\beta\) and \(\gamma\)). For instance, for \(\beta = \gamma = 1\), cooperation reduces downstream profits if and only if either \(n = 1\) and \(m \leq 10\), or \(m = n = 2\). Similarly, upstream profits are less for \(m = 1\) and \(n \geq 3\), and also for \(m = 2\) and \(n = 3, 4\). Simulations show that the problem is considerably exacerbated when downstream research is relatively more expensive at the margin, i.e., \(\gamma\) is larger than \(\beta\), and vice versa.

One way to make the cooperative R&D arrangement incentive compatible is to have the firms whose profits increase pay the losing firms a side payment. The side payment can be regarded as the former's contribution to establish, say, a research lab and then
invite the other firms to join in. An example of a side payment from a downstream to an upstream firm is the reported $2 million that Air Touch Communications (a downstream wireless personal communications services firm) gave Qualcomm (which pioneered a novel technical standard for digital compression) in 1991 to build a trial cellular network using their proprietary technology.\textsuperscript{7}

III.A R&D Semi-Cooperation

We refer to R&D cooperation in either one market tier, whether upstream or downstream, by semi-cooperation. Here cooperation serves to coordinate actions among rival firms on one (horizontal) level. This form of R&D cooperation, as is well-known in the literature, internalizes the negative externalities in firms' (horizontal) R&D decisions and hence will reduce the amount of R&D at the level of the market where cooperation takes place. As this happens, R&D at the other level of the market will also decrease, since upstream and downstream R&D are strategic complements as we showed earlier in this paper. We confirm this next.

Suppose that all the \( m \) upstream firms choose their R&D levels collectively to maximize their joint profits, whereas the downstream firms still make their R&D decisions independently, each investing \( y \). In this case, the upstream industry maximizes profit per firm given that all the upstream firms invest the same amount (\( x_i = x \) for all \( i \)). Thus it maximizes

\[
\pi^U - \beta x^2 = \frac{n}{n+1} \frac{(a - c_T - c_T + x + y)^2}{(m+1)^2} - \beta x^2
\]

over \( x \). From the first order condition, the (collective) upstream R&D best-response function is

\[
x = \frac{a - c_T - c_T + y}{\frac{\beta (n+1)(m+1)^2}{n}} = \frac{a - c_T - c_T + y}{mG(m,n) - 1}.
\]

\textsuperscript{7} For further details see “Not Exactly an Overnight Success” in BusinessWeek, June 2, 1997, pp. 132-4.
Comparing this equation with the R&D best-response function obtained under competition in Section 1.3 reveals that upstream R&D cooperation shifts the upstream R&D best-response curve downwards. This implies that in equilibrium, R&D in both upstream and downstream industries will decline relative to the case of competition. Similarly, it can also be established that semi-cooperation at the downstream level also reduces each firm’s R&D investment, whether upstream or downstream.

Section IV. Conclusions

The insights from the analysis of R&D among firms in a vertical relationship add considerably to those arising from the study of horizontal R&D alone since the latter do not capture the interaction between the market tiers. First, firms may only gain a relative cost advantage over their rivals under horizontal R&D. But with the introduction of the supplier-buyer relationship, R&D by a firm not only increases its cost advantage over its rivals, it may also raise their rivals’ absolute costs of production by increasing the demand for the input and thereby increasing the per-unit price they have to pay for it. Consequently increased competition in the upstream industry predictably reduces R&D at that level, but increased downstream competition may lead to a greater investment in R&D downstream due to the increase in rivals’ cost.

Second, we find a relationship that horizontal R&D models are unable to address: R&D investments at the two levels of the industry are strategic complements, implying that an increase in an upstream firm’s R&D induces all downstream firms to invest more in their cost-reducing outlays and vice versa. There are many consequences of this observation. For one, changes in research expenditures at one level of the market, say due to increased competition at that level, collective research, or government policy, will affect the R&D incentives at the other level as well. An increase in upstream competition for instance increases downstream R&D, and conversely. Additionally, firms may have incentives to
form vertical alliances in order to coordinate their R&D decisions.

Third, the policy implications arising from our two-tier model are different from those of horizontal R&D models. In our setting, cooperative R&D internalizes the positive externality between the two tiers of the market and thus can promote innovation even in the absence of spillovers, which is not the case in the horizontal R&D models. Put differently, cooperative R&D in horizontal models help to internalize the negative externalities at that level while ignoring that this cooperation may impose a negative externality on the other level of the market through a reduction in innovation outlays. This needs to be taken into account when evaluating government policies towards research joint ventures.

We conclude by mentioning two directions for future research. One is the incorporation of research spillovers (which could be both horizontal and vertical in nature) and its welfare consequences. Another is to look at the impact of competing vertical research joint ventures where upstream and downstream firms come together to undertake joint research. Such models will be crucial in formulating policy towards agro-biotechnology, for instance, where large chemical and pharmaceutical companies have formed competing vertical alliances as new transgenic products go from the pre-commercial phase of development to their commercial launch.

APPENDIX

Proof of Proposition 1: In establishing the results, it is convenient to treat \( m \) and \( n \) as real numbers even though they are integer-valued. Thus to establish (i), we show \( \frac{\partial z^*}{\partial m} < 0 \) for \( m \geq 2 \) and \( n \geq 1 \). It suffices to show that \( \frac{\partial G}{\partial m} > \frac{\partial (G/H)}{\partial m} \). Since \( \frac{\partial G}{\partial m} = \frac{(n+1)(m^2-1)}{nm} \) and \( \frac{\partial (G/H)}{\partial m} = \beta/[\gamma(n+1)] \), it follows that

\[
\frac{\partial G}{\partial m} > \frac{\partial (G/H)}{\partial m} \iff \gamma \frac{(n+1)^2(m^2-1)}{nm^2} > 1,\]

20
which is true for all $m \geq 2$ and all $n \geq 1$. Next we show that $x^*(1, n) > x^*(2, n)$. Since

$$G(1, n) - \frac{G(1, n)}{H(1, n)} = \frac{4\beta(n + 1)}{n} - \frac{\beta}{\gamma} \cdot \frac{2n^2 - 1}{n^2(n + 1)}$$

and

$$G(2, n) - \frac{G(2, n)}{H(2, n)} = \frac{9\beta(n + 1)}{2n} - \frac{\beta}{\gamma} \cdot \frac{1}{n^2(n + 1)}.$$

Since $\gamma(n+1)^2 > 2n$, the above expression is negative, establishing that $x^*(1, n) > x^*(2, n)$.

This proves (i).

To establish (ii), it is sufficient to show that $\Delta \equiv [G(m, n) - G(m, n)/H(m, n) - 1]/m$ decreases with $m$, i.e., $\partial \Delta / \partial m < 0$. From

$$\frac{\partial \Delta}{\partial m} = -\frac{\beta}{m^2} \cdot \left[ \frac{2(m + 1)(n + 1)}{mn} - \left( \frac{1}{\gamma} \frac{(n - 1)}{n^2} + \frac{1}{\beta} \right) \right],$$

it follows that the expression in the square brackets is always positive (the first term inside the square brackets is always greater than 2 for all $m, n \geq 1$ while the term within the curly brackets is always less than 2). This establishes part (ii).

To establish (iii), note that

$$y^*(m, n) = \frac{G(m, n)(a - c_L - c_T)}{H(m, n)G(m, n) - H(m, n) - G(m, n)}.$$

Hence

$$\frac{\partial y^*}{\partial m} = \frac{(a - c_L - c_T)\delta}{[H(m, n)G(m, n) - H(m, n) - G(m, n)]^2},$$

where

$$\delta \equiv -H \frac{\partial G}{\partial n} + G \frac{\partial H}{\partial n} - G^2 \frac{\partial H}{\partial n}.$$

Direct derivation of $\delta$, after algebraic rearrangement, reveals that $\delta < 0$ iff the following expression is positive:

$$\left( [n^2(m+1)-1](3n+1) - [2n^2(m+1)(n+1)] \right) \cdot \left( 1 + \frac{\beta(m+1)^2(n+1)}{mn} \right) - [n^2(m+1)-1].$$
It is possible to verify that in the worse case scenario where $\beta = 1$, the sign of this expression is negative for $n = 1$ and positive for $n \geq 2$. Hence $\frac{\partial y^*}{\partial m} > (\) 0$ for $n = (\) 1$, proving (iii).

The proof of part (iv) is similar to that of part (ii). To prove the first part of (v), it suffices to show $\frac{\partial y^*}{\partial m} > 0$ or that $\frac{\partial H}{\partial m} < \frac{\partial (H/G)}{\partial m}$. From

\[
\frac{\partial H}{\partial m} = -\frac{\gamma n(n + 1)^2(m + 1)[m + n^2(m + 1) - 1]}{m^2[n^2(m + 1) - 1]^2}
\text{and}
\frac{\partial (H/G)}{\partial m} = \frac{\gamma}{\beta} \cdot \frac{n^2(n + 1)(-n^2)}{[n^2(m + 1) - 1]^2},
\]

it follows that

\[
\frac{\partial y^*}{\partial m} > 0 \iff m^2 n^3 < \beta(n + 1)(m + 1)[m + n^2(m + 1) - 1]
\]

which clearly holds if $\beta \geq 1$.

Similarly, to establish the second part of (v), it suffices to show that $\frac{\partial x^*}{\partial n} > 0$, or $\frac{\partial G}{\partial n} < \frac{\partial (G/H)}{\partial n}$. It is straightforward to show that

\[
\frac{\partial G}{\partial n} = -\frac{\beta(m + 1)^2}{mn^2}\text{ and } \frac{\partial (G/H)}{\partial n} = \frac{\beta}{\gamma} \cdot \frac{-n^3(m + 1) + 3n + 2}{n^3(n + 1)^2}.
\]

Hence,

\[
\frac{\partial x^*}{\partial n} > 0 \iff \frac{(m + 1)^2}{m} > \frac{1}{\gamma} \cdot \frac{n^3(m + 1) - 3n - 2}{n(n + 1)^2}.
\]

The last inequality holds if $\gamma \geq 1$ because

\[
\frac{(m + 1)^2}{m} > (m + 1) > \frac{n^3(m + 1)}{n(n + 1)^2},
\]

concluding the proof of (v).

\textit{Proof of Proposition 2}: From equations (5) and (7), $x^C(m,n) > x^*(m,n)$ if and only if

\[
G(m,n) - G(m,n)/H(m,n) > \frac{\beta(m + 1)^2(n + 1)^2}{n(m + n + 1)} - \frac{\gamma n\beta}{n\gamma}
\]

\textit{22}
which, after algebraic rearrangement and simplification, can be rewritten as

$$\gamma n (m + 1)^2 (n + 1)^2 (mn - n - 1) < m (m + n + 1) (mn - n^2 + 1).$$

(11)

If \( n = 1 \), then inequality (11) becomes \( 4\gamma (m + 1)^2 (m - 2) < m^2 (m + 2) \) which obviously holds for \( m \leq 2 \). For \( m \geq 3 \), it is easily shown that

$$\frac{(m + 1)^2}{m^2} \cdot \frac{4(m - 2)}{m^2} > 1,$$

so that \( x^C(m, n) < x^*(m, n) \) for \( \gamma \geq 1 \). Therefore, for \( n = 1 \), \( x^C > x^* \) iff \( m \leq 2 \).

If \( m = 1 \), then inequality (11) becomes \( 4\gamma (n + 1)^2 > (n + 2) (n^2 - n - 1) \) which always holds for \( \gamma \geq 1 \) because

$$\frac{(n^2 - n - 1)}{(n + 1)^2} \cdot \frac{(n + 2)}{4n} < 1$$

for all \( n \). Thus \( x^C(1, n) > x^*(1, n) \) for all \( n \).

If \( m \geq 2 \) and \( n \geq 2 \), then \( mn - n - 1 > 0 \) and \( mn - n - 1 > mn - n^2 + 1 \). This implies that inequality (11) is reversed for \( \gamma \geq 1 \). So \( x^C < x^* \) for \( m \geq 2 \) and \( n \geq 2 \). This completes the proof of (i). The claims regarding downstream R&D \( y^* \) and \( y^C \) can be established analogously. \( \blacksquare \)
REFERENCES


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