A Model of Cooperative R&D Among Competitors

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ABSTRACT

Existing theoretical models of research joint ventures have influenced anti-trust policy but have several limitations. They suggest firms are more likely to cooperate when the technology is not highly appropriable, as in basic research. They also tend to ignore motivations associated with complementarity of skills and resources among potential participants as well as firm market share, while suggesting small firms may want to enter into joint ventures to pool resources and that anti-trust policy should permit this type of cooperation. We created an economic model that incorporates multiple factors. This suggests that, in the presence of high complementarity, firms are more likely to cooperate and more likely to succeed when the technology is highly appropriable, as in applied research. Our model also indicates large firms have a greater incentive to cooperate because they probably are better positioned to capture the benefits of a research venture. These findings seem to explain why cooperative research among rival firms in Japan has been applied rather than basic, conducted frequently among large companies, and relatively successful. But firms prefer as small a partner as possible to limit the sharing of research results, creating a tension that should make cooperative efforts among rivals difficult to manage. For this reason, cooperation through neutral organizations, such as universities or non-profit institutions, appears to be a useful alternative for rival firms wishing to pool R&D resources.

INTRODUCTION

A topic of increasing interest as a component of technology strategy and industrial as well as public policy has been cooperative research and development (R&D) not simply among suppliers and original equipment manufacturers -- who might collaborate with no conflict of competitive interest to develop particular products or technologies -- but among rivals in the same industry (Fusfeld and Haklisch, 1985; Ouchi and Bolton, 1988). The subject is far from new: Formal cooperative research was performed by the Chemical Manufacturers Association and the Motor Vehicle Manufacturers Association in the United States before 1900 (Batelle Memorial Institute, 1956), and by several engineering research associations (ERAs) in the United Kingdom prior to 1920 (Johnson, 1973). Informal cooperation among rivals, such as "know-how trading" (von Hippel, 1987 and 1988), may have an even longer history.

But cooperation as a way for rival firms, with or without government assistance, to pool resources to achieve greater or faster results than they might accomplish alone has become especially visible as a policy and strategic alternative with the success of several Japanese cooperative efforts in semiconductors, computers, and a wide range of other industries during the 1960s, 1970s, and 1980s (Patrick, 1986; Imai, 1986; Lynn, 1989). But while research joint ventures (RJVs) among rivals have proliferated in the United States and Europe in the form of several multi-million dollar programs (Peck, 1986; Mytelka, 1986; Toole, 1989; Samuels, 1987), government officials and managers concerned with antitrust as well as industry or firm competitiveness have had to evaluate increasing numbers of potential collaborative arrangements for their potential benefits and negative elements. Yet the available theoretical and empirical work on cooperative R&D remains confusing and provides few guidelines to aid in analysis or decision making, since guidelines that exist appear to be based upon models with only limited applicability.

For example, Bozeman, Link, and Zardkoohi (1983) describe a model of RJVs in which firms find it optimal to direct cooperative research towards the basic end of the R&D spectrum. In another influential paper, Katz (1986) shows that cooperative research is socially beneficial when the technology is not appropriable and when the agreement concerns basic rather than applied research. Grossman and Shapiro (1985) base a recommendation for antitrust policy on similar reasoning and suggest that governments should favor RJVs in areas of basic research. Rokuhara (1985) and Samuels (1987), on the other hand, have pointed out that most collaborative research in Japan -- where most of the successful cases seem to be -- is applied rather than basic and conducted frequently among large firms.

This paper examines company decisions to cooperate in research in a more general framework than in previous literature by taking into account the complementary skills and resources participating firms bring into an RJV. The model thus explains a broad range of successful and unsuccessful cases as well as suggests several non-intuitive results.

First, the model supports the notion that firms appear likely to cooperate in research areas with few expected benefits and technologies difficult to appropriate. This seems to have been a common rationale for encouraging or permitting collaborative efforts in basic research among rival firms within the U.S., few of which have been successful. However, the model indicates this type of collaboration will occur mainly in cases when participating firms have few complementary skills and resources. Hence, given few complementary skills and resources, as well as the difficulty of generating and appropriating benefits from basic research, the probability of success from these types of or too costly from the point of view of society, if patents limit the dissemination of knowledge. Subsidies may encourage investment in R&D, although economists widely consider these to be inefficient because subsidies interfere with market mechanisms. An RJV, on the other hand, as a mechanism to increase private incentives to innovate as well as the likelihood of success, appears to have numerous benefits.

Theoretical Benefits and Public Policy

The economic rationales for the existence and desirability of RJVs can broadly be grouped into three categories. First, RJVs can increase the efficiency of the R&D process by eliminating duplication of research effort, facilitating dissemination of technology, taking advantage of economies of scale or scope, and utilizing synergies by combining R&D capabilities of more than one firm. Second, by allowing firms to share costs (and/or risks), RJVs can make it possible for firms to undertake together costly (and/or risky) research projects that no firm would undertake alone. And third, RJVs can increase incentives to innovate by allowing firms to overcome the "free-rider" problem associated with R&D when patent protection is either imperfect or unavailable, as is often the case with basic research. In the absence of an RJV, firms may not be willing to invest in discovering knowledge that others could later utilize for free.

But RJVs can also harm competition by facilitating collusion among the participating firms. Ordover and Willig (1985) show that, under certain conditions, particularly when the market is expected to become highly concentrated, firms participating in an RJV may find it profitable to delay the realization of an innovation. Firms engaged in an industry-wide cooperative research effort to reduce costs may also find it optimal to slow down the rate arrangements should be low in theory and appears to be low in practice.

Second, the model indicates that favorable results from research joint ventures among rivals seem most assured when there is significant complementarity of skills and resources among the potential partners as well as greater likelihood of generating and appropriating benefits from the research. The model also indicates that successful cooperation is likely as long as a particular firm's share of the R&D costs in the joint venture is relatively low. Thus, contrary to views of collaborative efforts as ways for rival firms with small market shares or high costs to combine resources to conduct risky basic research more effectively, it appears that companies with large market shares and low-cost positions are more likely to cooperate and cooperate successfully than small firms. This is because the relative costs of a joint venture should be lower for bigger firms, while the larger firms may have an edge in exploiting any benefits from a joint effort due to their greater market positions.

COOPERATIVE R&D: THEORY VERSUS PRACTICE

R&D has long been recognized as an area of frequent market failure or frustrations in capturing benefits for the innovators, thus creating great incentives, even for rival firms, to cooperate in order to reduce risks and costs. For example, in an empirical study of seventeen innovations in the United States, Mansfield, Rapoport, Wagner, and Beardsley (1977) found that the rate of return to society far exceeded that to innovating firms. Firms, therefore, are likely to invest less in R&D than might be optimal for society in general. Tax incentives, subsidies, and the granting of patents and copyrights are among various mechanisms governments have used to provide additional incentives for firms to invest in innovation, although each has certain disadvantages.

For instance, patenting some innovations is either not feasible technically of R&D if industry demand is not very elastic (Katz, 1986). For example, in 1969, the Department of Justice brought an antitrust action against the four U.S.-based automobile manufacturers, prohibiting them from collaborating in the development of emission-control equipment for fear that the proposed venture was meant to delay development of the new technology (Yamamura, 1986).

White (1985) suggests that RJVs could also prove socially disadvantageous by reducing the number of research paths explored towards a solution and thereby either reducing the probability of success of an R&D project or increasing its cost. However, in the highly successful Very Large Scale Integrated Circuits (VLSI) project, the Japanese Ministry of International Trade and Industry (MITI) purposely assigned different firms to work on different ways of solving the same problems. Such a multifaceted, coordinated attack might not have occurred or occurred as rapidly in the absence of cooperation (Sakakibara 1983).

Overall, economists appear nearly unanimous in the opinion that RJVs are likely to be socially beneficial in areas when the technology is less appropriable such as with basic research. Not surprisingly, this thinking has had tremendous impact on the antitrust laws relating to the RJVs and consequently on the occurrence of RJVs in the U.S. Although U.S. government officials appeared to grow increasingly tolerant of collaborative efforts during the 1980s, in the 1980 antitrust guidelines, the Department of Justice took the position that "the closer [any] joint activity is to the basic end of research spectrum ... the more likely it is to be acceptable under anti trust law" (Department of Justice, 1980, p. 3). Even the more recent National Cooperative Research Act of 1984 (P. L. 98-642) "permits joint research and development ventures for the purpose of theoretical analysis, experimentation, or systematic study of phenomenon or observable facts." The Department of Justice has thus tended to approve RJVs among rivals primarily when they seemed beneficial to society at large and did not unduly restrain competitive behavior. This scrutiny discouraged firms who might otherwise have participated in an RJV. For example, the Senate Judiciary Committee noted in a 1984 investigation that antitrust challenges have been "frequently cited by industry to explain the reluctance to undertake such [cooperative research] activity" (U.S. Code Congressional and Administrative News, 1984, p. 3106).

Empirical Studies of RJVs

Not surprisingly, cooperative research among competitors in the U.S. has largely been confined to areas of basic research and studies related to health and safety conducted by industry research associations (Batelle Memorial Institute, 1956). Johnson (1973) reports a similar pattern of joint research activity in the United Kingdom. Recently established research efforts -- the Semiconductor Research Corporation, the Microelectronics and Computer Technology Corporation (MCC), and Sematech in the United States, as well as programs such as Alvey in the United Kingdom, the European Strategic Program for Research and Development in Information Technology (ESPRIT), and the European Research Coordination Agency (EUREKA) -- continue to emphasize basic research though with increasing amounts of applications (Mytelka, 1986; Alic, 1986; Toole, 1989). Cooperative research among competitors in applied areas especially thus represents a relatively new development in Western economies. Furthermore, even when U.S. government officials have encouraged cooperative R&D as well as production operations, as in the case of the now-defunct U.S. Memories joint venture or other proposals to develop high-definition television, managers have often appeared confused over how to evaluate the potential benefits of collaboration and, accordingly, reluctant to commit financial resources (Pollack, 1990).

In contrast, Japanese cooperative research efforts among rivals have a relatively long history. Yet, even in Japan, successful collaboration among rival firms appears to stem less from any specific cultural feature of the Japanese than from the focus of particular RJVs on applied research and the size (and thus potential skills and resources as well as market power) of collaborating firms. For example, in a comprehensive survey of collaborative efforts in more than 200 large and small firms across six sectors in Japan, Rokuhara (1985) found that, contrary to the belief popular among economists, less than 14% of inter-firm collaboration in Japan was directed at basic research. One third of all such collaboration could be defined as applied and over half could be considered development. Moreover, unlike the U.S., where large firms appeared reluctant to cooperate with rivals either because of antitrust concerns or uncertain benefits, in Japan, large firms were twice as likely to contract for joint research as small firms.

Studies by Anchordoguy (1989) and Cusumano (1990), which document cooperative research in Japan's computer industry, support this line of argument. As summarized in Table 1, MITI has sponsored RJVs in both hardware and software. Nearly all of the most successful collaborations occurred in the area of computer hardware, where the technology was highly appropriable by individual participating firms. For example, the VLSI project, reported to be the most successful collaborative effort among rivals, resulted in nearly 1,000 patents to the participants as well as helped Japan's large electronics producers (Fujitsu, NEC, Hitachi, Toshiba, and Mitsubishi) become leading worldwide producers of semiconductor memories and other devices used in commercial computers and related products. At the same time, MITI's efforts to get Japanese firms together to develop software products -- where the technology turned out to be less developed and more difficult to appropriate -- led to a series of embarrassing failures.

Insert Table 1 about here

Existing theoretical models thus do not adequately explain the character of successful collaborative RJVs among rivals in Japan or the reasons why firms might succeed or fail in these efforts, within Japan or elsewhere. The model of RJVs presented and discussed in the next sections provides a more general framework as well as suggests specific propositions for managers and policy makers.

RESEARCH JOINT VENTURES AS A GAME

A firm's decision to invest in an R&D project depends not only on its own motives and capabilities and on the nature of the project, but also on the motives and capabilities of its rivals. Game theory that explicitly considers the strategies available to competitors, therefore, appears to be an appropriate framework for analyzing a firm's R&D decisions. Previous game theoretic models of R&D (for instance, Gilbert and Newbury, 1982) focused on the resulting equilibrium level of investment in R&D by different firms. We, on the other hand, concentrate on the firm's decision -- whether to cooperate in a particular R&D project or not, with whom, and under what circumstances. We will therefore consider a specific R&D project with a known investment requirement but not consider the level of investment in R&D, an approach that simplifies the analytical formulation of the model without affecting the validity of the results.

The Model

We consider an industry with n firms ($i = 1, 2, \ldots, n$) whose costs (c_1, c_2, $\ldots$, c_n) are unequal. Define $c = (1/n)\Sigma c_i$ as the mean cost of firms in the industry. These firms produce a homogeneous product in an industry with a demand function $Q = Q(P)$, where Q is the industry output and P is the price. All firms in the model behave non-cooperatively, each maximizing its total expected profit constrained by the decisions of all other firms.

At issue in this model is the question of investment in a research project that would require R dollars of investment. This project is expected to reduce the marginal cost of production by a factor of B. That is, the marginal cost of production of firm i with cost c_i after successful R&D would be $c_i(1 - B)$. $B \in (0, 1)$ is a random variable with mean b and variance s^2.

In this game, firms choose whether to participate in an RJV for the particular research project or to do R&D on their own. Then the results of R&D, which are stochastic, become known. For simplicity, we assume that there is at most only one RJV in the industry working on the particular R&D project, though this assumption will in no way affect the validity of our results in the more general case of several RJVs within the industry for the particular R&D project. Let k ($\leq n$) firms in the industry choose to cooperate in the research project. The other firms ($n - k$) choose to do research on their own. Each of the k cooperating firms invests $y_i R$ dollars in research on the project, where y_i is the share of the project financed by the *i*th firm [$\Sigma y_i = 1$; $i \in (1, k)$]. The other firms ($n - k$) invest R dollars each on the project.

The R&D project we are considering is in the nature of a patent race in which there is always one and only one winner (see Reinganum 1984 for similar patent races). The probability of success of firm j doing research on its own is

p_j. The probability of success of the cooperative venture (treated in the model as a single entity doing research) is p. We define a complementarity factor g_i by the relation

$$p = g_i p_i; \; g_i \in (0, 1/p_i) \tag{1}$$

If cooperating firms bring complementary skills and resources to the RJV, then the probability of success of the RJV may be significantly higher than that for a member firm i proceeding alone. In this case the complementarity factor for firm i will be significantly higher than one. On the other hand, organizational difficulties could conceivably arise in combining personnel from different organizations and locations with different cultures and objectives (Harrigan, 1983) that might reduce the probability of success of the RJV to a level below that of a member firm i proceeding alone. The complementarity factor for firm i in such a case will be less than one. In general, the complementarity factor will be different for different firms in the same RJV.

Because the R&D project that we are considering is in the nature of a patent race, if all firms in an industry cooperate, then the probability of success of the venture will be one and the complementarity factor will be equal to or greater than one for all firms, *i.e.* $g_i \geq 1 = 1/p_i$ for all i.

<u>Profitability of a Cooperating Firm:</u> If the joint venture is successful, then the cooperating firms produce at a lower cost of

$$c_i' = c_i(1 - B) \tag{2}$$

where $i \in (1, k)$. In addition, the cooperating firms may also receive revenue from licensing the innovation to the other (n - k) firms in the industry who did not succeed. The expected profit of a cooperating firm under these conditions is:

$$E[\Pi_i] = E[\{P - c_i(1 - B)\}q_i + z_i acB\Sigma q_j - y_i R] \tag{3}$$

where $i \in (1, k)$; $j \in (k + 1, n)$ and:

i. $a \varepsilon (0, 1)$ is the appropriability factor. If the results of research are completely appropriable, for instance, in case of perfect patent protection, then $a = 1$. If the results are not appropriable at all, then $a = 0$.

ii. acB is the royalty per unit of sale which depends upon the appropriability factor, the mean cost of firms in the industry, and the benefit produced by R&D. The royalty is the same for all firms in an industry.

iii. z_i is the share of the *i*th cooperating firm in the royalty obtained from competitors not participating in the joint venture. $\Sigma z_i = 1$; $i \varepsilon (1, k)$.

If the cooperative venture is not successful but one of the non-cooperating firms succeeds, then each of the k cooperating firms obtains a license from the successful firm to produce at the unit cost of

$$c_i' = c_i(1 - B) + acB \quad (4)$$

The expected profit of the firm in this case is:

$$E[\Pi_i] = E[\{P_2 - c_i(1 - B) - acB)\}q_i - y_iR] \quad (5)$$

Combining (3) and (5), the profit of a cooperating firm is given by:

$$E[\Pi_i] = E[p\{(P - c_i(1 - B))q_i + z_iacB\Sigma q_j\} + (1 - p)\{(P - c_i(1 - B) - acB))q_i\}] - y_iR \quad (6)$$

<u>Profitability of a Non-cooperating Firm:</u> If a non-cooperating firm j is successful, then it produces at a cost of:

$$c_j' = c_j(1 - B) \quad (7)$$

In addition, the firm receives revenue from licensing the innovation to the other (n - 1) firms in the industry who did not succeed. Its total expected profit is:

$$E[\Pi_j] = E[\{P - c_j(1 - B)\}q_j + acB\Sigma q_i - R] \quad (8)$$

where $i \varepsilon (1, n)$; $j \varepsilon (k + 1, n)$; $i \neq j$.

If firm j is not successful, then it obtains a license from the successful firm to produce at the unit cost of

$$c_j = c_j(1 - B) + acB \tag{9}$$

Its expected profit in this case is:

$$E[\Pi_j] = E[\{P - c_j(1 - B) - acB\}q_j - R] \tag{10}$$

Combining (8) and (10), the profit of a non-cooperating firm is given by:

$$E[\Pi_j] = E[p_j\{(P - c_j(1 - B))q_j + acB\Sigma q_i\} + (1 - p_j)\{(P - c_j(1 - B) - acB)q_j\}] - R \tag{11}$$

Equations (6) and (11) can be combined to yield a single objective function for all the firms in the industry:

$$\text{Max } E(\Pi_i) = E[(P - c_i')q_i + x_i(z_i pacB\Sigma q_j - y_i R) + (1 - x_i)(p_i acB\Sigma q_m - R)] \tag{12}$$

where $i \varepsilon (1, n)$; $j \varepsilon (k + 1, n)$; $m \varepsilon (1, n)$; $j, m \neq i$; x_i is an indicator variable that takes the value of 1 when the firm is cooperating in research and is zero otherwise. The value of c_i' is given by equations (2), (4), (7) and (9) with probabilities p, (1 - p), p_i, and $(1 - p_i)$ respectively.

Existence and Uniqueness of Equilibrium

The solution concept we use is that of Cournot-Nash equilibrium. A non cooperative Nash equilibrium of the above game is $\{Q^* = \Sigma q_i^*\}$; which simultaneously solves problem (12) for all firms. That is, at Q^*

$$E[\Pi_i^*] = \text{Max } E[\Pi(q_1^*,\ldots,q_i,\ldots,q_n^*)|(q_1^*,\ldots,q_{i-1}^*,q_{i+1}^*\ldots,q_n^*)]$$

where n is the number of firms producing positive output in the industry.

Rosen (1965) has demonstrated that a sufficient condition for the existence and uniqueness of industry equilibrium in such a case is that the symmetric matrix $[G(P,q) + G'(P,q)]$ be negative definite, where $G(P,q)$ is given by the Jacobian of the gradient of firms' objective functions:

$$\begin{bmatrix} 2P^1+P^{11}q^1 & P^1+P^{11}q_1 & \ldots & P^1+P^{11}q_1 \\ P^1+P^{11}q^2 & 2P^1+P^{11}q_2 & \ldots & P^1+P^{11}q_2 \end{bmatrix}$$

$$G(P,q) = \begin{bmatrix} \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ P^1+P^{11}q_n & P^1+P^{11}q_n & \cdots & 2P^1+P^{11}q_n \end{bmatrix} \quad (13)$$

where superscripts denote derivatives. We assume throughout that condition (13) is satisfied. A sufficient condition for this to be true requires that P^{11} be bounded from above by a function of P^1 (Flaherty, 1980), as the determinants of the minor of G(P,q) alternate in sign if $P^{11}(q_i + q_j)$ is small enough relative to $(P^1)^2$. In particular, condition (13) is satisfied if P is linear.

We can now invoke Kakutani's fixed point theorem to prove the existence of equilibrium in this model. We consider only those firms in the industry which are producing positive outputs, *i.e.*, for which $P(Q) > c_i$. The first order condition for (11) is

$$P(Q) - c_i' + P^1(Q)q_i = 0 \quad (14)$$

From which

$$q_i = -[P(Q) - c_i']/P^1(Q) = F(q_i, c_i'), \text{ say.} \quad (15)$$

where $q_i = \Sigma q_j$ is the sum of outputs of all firms, except firm i, producing positive output in the industry.

Let $F(Q, c) = (F_1(q_1, c_1'), \ldots, Fn(q_n, c_n'))$, where $c = \Sigma c_i'$. F(Q, c) is continuous in Q and c which form compact and convex sets. $q_i \in (0, q_{max})$, and $c_i \in (c_{min}, c_{max})$ form compact and convex sets. Therefore, from Kakutani's (1941) fixed point theorem there exists a Q^* for which $q_i^* \in (0, q_{max})$.

Taking the sum of (14) for all firms in the industry at the equilibrium output,

$$np(Q^*) - c + Q^*P^1(Q^*) = 0 \quad (16)$$

The left hand side of (16) is monotonically decreasing in Q^*. It can reach the value of zero only at one point. The industry equilibrium is therefore unique.

<u>Profitability of Firms at Equilibrium:</u> At equilibrium output we obtain

firm's expected profit from (12) by substituting for q_i from (15):

$$E[\Pi_i] = E[-\{(P - c_i')^2/P^1\} + x_i(z_i pacB\Sigma q_j - y_i R) + (1 - x_i)(p_i acB\Sigma q_m - R)] \quad (17)$$

Substituting in (17) for c_i' from equations (2) and (7) with probabilities p and (1 - p) respectively, the profit of a cooperating firm is:

$$E[\Pi_i] = E[p\{-(P - c_i(1 - B))^2/P^1 + z_i acB\Sigma q_j\} + (1 - p)\{-(P - c_i(1 - B) - acB)^2/P^1\}] - y_i R \quad (18)$$

Substituting in (17) for c_i' from equations (4) and (9) with probabilities p_i and $(1 - p_i)$ respectively, the profit of a non-cooperating firm is:

$$E[\Pi_j] = E[p_j\{-(P - c_i(1 - B))^2/P^1 + acB\Sigma q_j\} + (1 - p_j).\{-(P - c_i.(1 - B) - a.c.B)^2/P^1\}] - R \quad (19)$$

Taking expectation, the profit of a cooperating firm is given by:

$$\Pi_i = p\{-((P - c_i(1 - b))^2 + c_i^2 s^2)/P^1 + z_i acb\Sigma q_j\} + (1 - p)\{-((P - c_i(1 - b) - acb)^2) + (c_i^2 + a^2c^2)s^2)/P^1\}] - y_i R \quad (20)$$

And the profit of a non-cooperating firm is given by:

$$\Pi_j = p_j\{-((P - c_j(1 - b))^2 + c_j^2 s^2)/P^1 + acb\Sigma q_i\} + (1 - p_j)\{-((P - c_j(1 - b) - acb)^2 + (c_j^2 + a^2c^2)s^2)/P^1\}] - R \quad (21)$$

RESULTS FROM THE MODEL

We can now compare (20) and (21) to see which factors would favor formation of an RJV. We consider the case of two firms i and j with similar costs ($c_i = c_j$) and probabilities of success in R&D if doing research alone ($p_i = p_j$). Firm i participates in the RJV and firm j does not. We are interested in knowing which of the two firms would be more profitable and under which conditions. The firm that cooperates is more profitable if

$$E[\Pi_i] - E[\Pi_j] > 0.$$

Substituting from (20) and (21), and using from (1) the fact that $p = g_i p_i$, we obtain after some algebra:

$$E[\Pi_i] - E[\Pi j] = R(1 - y_i) + p_i abc(g_i z_i \Sigma q_m - \Sigma q_h)$$
$$- (ac/P^1)\{2b(P - c_i(1 - b)) - acb^2 - acs^2\}\{p_i(g_i - 1)\} \qquad (22)$$

where m ε (k + 1, n); i, j, h ε (1, n); i ≠ h.

In equilibrium, the value of (22) is non-negative for every firm i participating in the RJV. The first term on the right hand side of (22) is always non-negative as $y_i \leq 1$. The first part of the last term on the right hand side of (22) is the difference between the non-royalty profits of a firm in case of successful and unsuccessful R&D and is also non-negative, *i.e.*,

$$- (ac/P^1)\{2b(P - c_i(1 - b)) - acb^2 - acs^2\} \geq 0 \qquad (23)$$

This assumes that a firm's cost in the case of successful R&D is never higher than what it would be in the case of unsuccessful R&D and $\partial\Pi/\partial c < 0$. The sign of (22), therefore, depends critically on the value of the second term on the right hand side of (22) and on the value of g_i. If organizational difficulties reduce the complementarity factor for firm i to below unity ($g_i < 1$), then both the second and the third terms on the right hand side of (22) are negative and the sole benefit from cooperation to firm i is financial (*i.e.* cost sharing). In such a case, firm i may be better off financing the R&D through another source. Also, if $g_i < 1$, then the probability of success of firm i doing R&D alone is higher than that of the RJV and other members of the RJV will be better off by limiting their collaboration to the area of finance and leaving firm i alone to do research on their behalf. In equilibrium, therefore, we should expect g_i to be greater than unity for all firms in an RJV. We now present our key results in the form of a series of simple propositions and proofs.

Proposition 1: Other things being equal, a firm will prefer to cooperate in research if the complementarity of skills and resources among the partners is high.

Proof: Differentiating (22) with respect to g_i we get:

$$\partial[E(\Pi_i) - E(\Pi j)]/\partial g_i = p_i abcz_i \Sigma q_m - \{2b(P - c_i(1 - b)) - ac(b^2 + s^2)\}acp_i/P^1 \qquad (24)$$

From (23), the second part of the above equation is always non-negative. Since the first part of (24) is always positive, we have,

$$\partial[E(\Pi_i) - E(\Pi j)]/\partial g_i \geq 0$$

The effect of complementary skills or resources on the profitability of an RJV relative to that of a single firm doing research on its own is always positive.

Proposition 2: Other things being equal, firms will prefer to cooperate if the cost of an R&D project is high.

Proof: Differentiating (22) with respect to R, the cost of the R&D project,

$$\partial[E(\Pi_i) - E(\Pi j)]/\partial R = (1 - y_i) \geq 0 \text{ as } y_i \leq 1.$$

Proposition 3: Other things being equal, the smaller a firm's share in the total cost of the R&D project, the more likely it will be to cooperate in research.

Proof: Differentiating (22) with respect to y_i,

$$\partial[E(\Pi_i) - E(\Pi j)]/\partial y_i = - R \leq 0.$$

Corollary: The larger the subsidy (from the government) towards the cost of the cooperative R&D project, the more likely a firm will be to cooperate.

Proof: A subsidy has the effect of reducing a firm's share in the total cost of the R&D project, y_i, and, to this extent, it encourages cooperation.

Proposition 4: The larger a firm's share in expected royalties the more likely it will be to cooperate in research.

Proof: Differentiating (22) with respect to z_i,

$$\partial[E(\Pi_i) - E(\Pi j)]/\partial z_i = p_i abcg_i \Sigma q_m \geq 0.$$

Corollary: A firm may want to cooperate with many partners if an increase in the number of participants will reduce its share in the cost of the R&D

project more than it will reduce its share in expected royalties.

Proof: An increase in the share of R&D cost reduces expected profits from cooperative research, while an increase in the share of expected royalties increases expected profits. These are opposing effects. As the number of partners in the joint venture increases, the share of costs to be borne by a firm decreases but its share in potential royalties also declines. If all k firms in the joint venture share cost and royalties equally then $y_i = z_i = 1/k$, and

$$\partial[E(\Pi_i) - E(\Pi j)]/\partial k = (R - p_i acbg_i \Sigma q_m)/k^2$$

The above expression is positive if the cost of R&D is high. It is negative if the expected royalties from non-cooperating firms are large. If the cost of R&D is high, then an increase in the number of participants in the joint venture increases the expected profits as it reduces the cost of R&D to a firm. But if the royalties expected from R&D are high because of a high probability of success in R&D if the firm were to do research alone or with fewer partners, appropriability of the technology, or large expected benefits from research, then an increase in the number of participants may lower the expected profits of the firm. This latter effect may, however, be small in magnitude for firms with large market shares, for whom the output of non-cooperating firms, Σq_m is small. Firms with large market shares, therefore, may have a relatively greater tolerance for a larger number of partners in an RJV.

Proposition 5: If the complementarity factor of a firm is greater than unity, then, other things being equal, the lower the cost of a firm the more likely it will be to cooperate in research.

Proof: Differentiating (22) with respect to c_i,

$$\partial[E(\Pi_i) - E(\Pi j)]/\partial c_i = 2p_i acb(1 - b)(g_i - 1)/P^1 \leq 0 \text{ for all } g_i > 1,$$

because $P^1 \leq 0$. In our model of Cournot competition among asymmetric firms, the low-cost firm will have a higher market share in equilibrium [see equation

(15)]. Thus, the above proposition means that a firms with a large market share will have a greater incentive to participate in an RJV. A low market share firm will have correspondingly smaller incentive to participate in an RJV.

Proposition 6: Other things being equal, a firm will prefer as small a partner in an RJV as possible.

Proof: We can rewrite (22) by splitting Σq_h, the output of all competitors of firm i, into two parts comprising the output of the competitors cooperating in the RJV, Σq_u, and the output of firms doing research on their own, Σq_m.

$$E[\Pi_i] - E[\Pi j] = R(1 - y_i) + p_i abc(g_i z_i \Sigma q_m - \Sigma q_m - \Sigma q_u)$$
$$- \{2b(P - c_i(1 - b)) - acb^2 - acs^2\}\{acp_i(g_i - 1)\}/P^1 \qquad (25)$$

Differentiating (25) with respect to Σq_u, the output of the partners of the *i*th firm in the RJV,

$$\partial[E(\Pi_i) - E(\Pi j)]/\partial \Sigma q_u = - p_i acb \le 0.$$

Proposition 7: In the absence of significant complementarity of skills and resources, firms will prefer to cooperate in research in areas where the expected benefits are small and/or the technology is less appropriable. But in the case of significant complementarity of skills and resources among the partners, firms will prefer to cooperate in research in areas where the expected benefits are high and/or the technology is highly appropriable.

Proof: Differentiating (22) with respect to b, the benefits from the R&D project in terms of expected per unit cost reduction,

$$\partial[E(\Pi_i) - E(\Pi j)]/\partial b = p_i ac(g_i z_i \Sigma q_m - \Sigma q_h)$$
$$- [\{P - c_i(1 - b)) - bac\} + bc_i]2p_i ac(g_i - 1)/P^1 \qquad (26)$$

If $g_i \le 1$ then both the first and the second terms on the right hand side of (26) are negative. In case of low complementarity, therefore, firms will prefer to cooperate in areas where the expected benefits from research are small.

But if $g_i > 1$, then the second term on the right hand side of (26) is positive. The value of (26) therefore depends on the first term on the right hand side of (26). If the complementarity of skills and resources is quite high, particularly if g_i is so large that $g_i z_i \Sigma q_m > \Sigma q_h$, then the value of (26) is likely to be positive. That is, in the presence of highly complementary skills and resources, the above result is reversed and firms prefer to cooperate in research in areas where the expected benefits from research are high.

To investigate the effect of appropriability, we consider equation (22) again. If $g_i \leq 1$ then, from (23), the second and the third terms on the right hand side of (22) are negative. As the absolute value of the second term on the right hand side of (22) is increasing in a, for any given level of cost of R&D and for any given set of partners, firms will prefer to cooperate in an area where a is small. In case of low complementarity, therefore, firms will prefer to cooperate in areas where the technology is less appropriable.

If $g_i > 1$ then, from (23), the first and the third terms on the right hand side of (22) are always non-negative. The value of (22) therefore depends on the second term on the right hand side which is positive if the complementarity of skills and resources is so large that $g_i z_i \Sigma q_m > \Sigma q_h$. This means that, for any given cost of R&D, if the complementarity of skills and resources is very high, then firms will prefer to cooperate in an area where the technology is highly appropriable. This effect is further enhanced if the partners of a firm are small.

Proposition 8: When $g_i > 1$, an RJV will nearly always increase consumer welfare, except where all or most of the firms in an industry participate in it and industry demand is not very elastic.

Proof: If $g_i > 1$, then the RJV increases the probability of success of an R&D project. In the absence of collusion, the R&D project always results in lower costs for one or more firms in the industry and in higher costs to none. As a result, industry prices fall, output goes up, and consumer welfare increases, whether the successful firm participates in the RJV or not. However, if all or most firms in the industry participate in the RJV and demand is not very elastic, then consumers receive most of the benefit from cost reduction and firms have less incentive to reduce costs. An RJV in such a case may present firms the opportunity to collude and slow down the rate of R&D (Katz, 1986).

DISCUSSION OF RESULTS

Previous models of RJVs suggested that firms were likely to cooperate in research in areas where the cost of R&D was high, where the expected benefits from research were small, and where the technology was less appropriable, such as in the case of basic research. These analyses, however, did not consider variables such as complementarity of skills and resources as well as market shares. In this section, we first discuss the public-policy and management implications of complementarity of skills and resources of firms in an RJV and then outline the strategic implications for the managers of firms participating in RJVs.

Complementarity and Proprietary Benefits

Complementarity of skills and resources appears to be the most important factor influencing a firm's decision to participate in an RJV in our model as it mediates the effects of factors such as the expected benefits from research and the appropriability of technology. If the complementarity of skills and resources brought to a venture by the participating firms is low, then the results from our model are similar to those obtained by earlier models in which firms prefer to cooperate in areas where the expected benefits from research are small and where the technology is less appropriable. But if firms have complementary skills and resources that may increase the probability of success of the RJV well beyond the probability of success of a single firm conducting research on its own, then firms will prefer to cooperate in areas where the expected benefits from research are high and the technology is highly appropriable.

Figure 1 shows the interaction of complementary skills and resources of firms participating in an RJV with the expected benefits from research and the appropriability of technology. The vertical axis represents a multiplicative combination of the expected benefits from research and the appropriability of technology, which might be called the expected proprietary benefits from research. The horizontal axis represents complementarity of skills and resources measured by the increase in the probability of success of an RJV beyond the probability of success of a single firm acting alone. The combination of these factors results in four fundamentally different types of RJVs represented by the four quadrants in Figure 1. The RJVs in these quadrants differ in the likelihood of their occurrence, in the probability of their success, and in the motives behind their formation.

Insert Figure 1 about here

Quadrant I: RJVs in this quadrant are characterized by high levels of complementary skills and resources as well as high proprietary benefits. Almost by definition, then, they involve projects relatively close to commercial applications, with sufficiently clear or focused topics so that firms can effectively bring together skills and resources, even though individual companies are still responsible for commercialization of the research results. This type of cooperation seems to describe much of the successful research among rival Japanese firms (Rokuhara, 1985; Samuels and Levy, 1989), for example, in semiconductors (Sakakibara, 1983), computer hardware (Anchordoguy, 1989), biotechnology (Saxonhouse, 1986), and aerospace (Samuels and Whipple, 1988)

An extreme case of complementarity occurs when all or most firms in an industry cooperate. The probability of success of such an RJV is nearly one and the complementarity factor is high for most participants. Such RJVs may be expected to be nearly always profitable. The large number of industry wide cooperative efforts to set up standards falls in this category. The probability of one firm setting an industry standard on its own is small, though not impossible, as in the case of computer mainframes (IBM's Systems 360 and 370) or video recorders (Japan Victor's VHS standard), but the probability of success increases significantly if most firms in an industry cooperate.

Quadrant II: Projects that fall into this quadrant are characterized by high complementarity of skills and resources but low expected benefits from research, due to low appropriability of the technology, as in the case of focused but still basic technology development. These projects may also include applied areas where patents would be difficult or unwise to obtain, perhaps because the technology involved is difficult to specify precisely, as in some manufacturing processes, or the knowledge may be useful for various firms only in certain contexts, so companies feel little need or ability to protect it.

Accordingly, while firms pursuing cooperation within Quadrant I might actively seek formal partnerships on their own or with minimal encouragement from government, because of high expected benefits and highly appropriable technology, for Quadrant II projects, one might expect either modestly subsidized efforts in basic research among firms that appear to have complementary skills as well as loosely structured strategic alliances or relatively informal cooperation among firms to develop specific but not particularly appropriable technologies. The latter would include instances of informal know-how trading, such as in steel manufacturing or other processes, described by von Hippel (1987, 1988) and Schrader (1989).

Quadrant III: Projects in this quadrant are characterized by low complementarity of skills and resources, such as when research objectives are unclear and participants are unable to complement one another, as well as by low proprietary benefits, such as in the case of basic research or applications difficult to patent. These types of cooperative efforts should be the least desirable from the point of view of managers and policy makers because they are least likely to bring any benefits to the participants or to society at large. Project planners or champions would probably be very unlikely to agree in advance that their efforts were likely to fall into Quadrant III, although the model encourages managers and policy makers to assess realistically the potential complementarity of skills and resources among the participants as well as the potential outcomes of a project. When both inputs and outputs seem vague or difficult to patent or apply, the project is very unlikely to succeed and may not be worth pursuing.

The characteristics of RJVs in this quadrant give rise to two concerns. First, since basic research is necessary for technological progress and returns to society in general may be very high, even if individual firms may find basic research difficult to appropriate benefits from, to what degree should governments actively subsidize RJVs that would fall into this unattractive quadrant? And second, what is the preferred organizational arrangement for conducting R&D projects unlikely to succeed or at least have short-term applications?

The answers to these two questions are related. If there are only a few firms in an industry among whom coordination could be achieved easily, then a subsidy tied to performance and monitored closely may be socially beneficial.

But the case for subsidy in absence of coordination is weak. Firms should cooperate on RJVs in this quadrant on their own. If they do not, then they probably have more attractive R&D options. If such firms are brought together by a subsidy, then they will have an incentive to limit their participation. If there are several firms in an industry among whom coordination may be difficult, then research initiatives independent of individual firms, such as through industry or trade organizations, or universities, may be better vehicles to carry out the research program.

Quadrant IV: Large expected benefits from research due to high appropriability of technology but low complementarity of skills and resources among the partners characterize RJVs in this quadrant. In these types of efforts, firms probably cooperate primarily for monetary reasons -- combining financial resources to fund development of a promising new product or process that seems patentable or easily made proprietary, even though the participants do not possess, at least initially, complementary technical skills.

For example, developing new products and processes is extremely expensive in industries such as aerospace and telecommunications. The cost of developing a new aircraft engine is estimated at over $1.5 billion and that of developing certain computerized digital switches at over $1 billion (Hladik, 1988). Sharing costs or risks, therefore, might provide a strong motivation for cooperation even among rival firms. However, RJVs should not be regarded as substitutes for capital markets. A firm that can carry out a research project in this quadrant without assistance may be better off obtaining funds on its own. This probably explains the failure to get rival firms to cooperate when individual companies have the technical skills and financial resources to proceed alone, even at considerable risk, and the technology is highly appropriable, but the market size or growth and thus financial returns from cooperation are also unclear.

Market Share and Partner Size

The existing literature on RJVs is silent about the differences between the motives for cooperation of large and small firms. In our model, the large market-share firm has a greater incentive to cooperate with industry rivals than a small firm. The reasons are as follows: Sharing costs in an RJV entails sharing income from royalties, but royalties should be relatively less important to the large market-share firm, which stands to gain more non-royalty profit from a reduction in production costs or other innovations because of its large output. This is also the reason why the large market-share firm should have a greater tolerance for numerous partners in an RJV.

The above result accords well with the frequency with which the names of market leaders such as General Electric, AT&T, Phillips, Siemens, Boeing, and United Technologies (Pratt and Whitney Division) appear in the literature on RJVs (Hladik, 1988). In Japan as well, while Rokuhara (1985) found instances of small firms pooling resources, large Japanese firms more often participated in RJVs. In fact, thirty large Japanese firms accounted for one third of the membership in all government-sponsored research associations (Samuels, 1987), leading Samuels to conclude that large firms, with a variety of internal capabilities, were best positioned to take advantage of an RJV. Johnson (1973) documented similar findings in the United Kingdom, where engineering research associations initially established to assist small firms eventually derived their main support from large companies.

In our model, for any given level of complementarity of skills and resources, and for any rule governing the sharing of R&D expenses and potential royalties, firms also prefer as small a partner as possible. A decision to participate in an RJV means the potential loss of royalties from rival firms participating in the venture, and this is small if the partners are small. An ideal partner will thus not be an industry rival but bring complementary skills and resources with zero market share. The frequent collaborative research efforts between large firms and universities or non-profit research institutions are examples of this type of non-rival cooperation and seem to represent a practical alternative for R&D partnerships. Indeed, managers seem to have recognized this already, as discussed in Mytelka (1986), who reported that, in the U.S. between 1967-1977, industry-sponsored university and non-profit research expanded two-thirds faster than in-house company research.

Yet the attraction of RJVs for large firms and the preference of firms for as small a partner as possible present difficulties for firms wishing to establish RJVs within an industry. An RJV comprising the largest firms is not the most desirable one from the point of view of participants. Left on its own, a large firm will prefer a small partner that would nevertheless bring in complementary skills and resources. But our model suggests that a small firm with the skills and resources to carry out research on its own has merely a small incentive to participate in an RJV with a large rival, hence the difficulty in achieving an ideal configuration of partners in an RJV. Uneasy alliances are bound to occur in which the mutual expectations of partners will not be fulfilled. This realization may account for the frequent problems that arise in the management of RJVs in general and their high rate of failure (Harrigan, 1983).

CONCLUSION

Our goal in this paper has been to model a firm's decision to cooperate in research with industry rivals not simply to evaluate antitrust policy but to provide insights into a number of conflicting decisions and compromises that managers of firms participating in or contemplating RJVs must face. We demonstrated that the results from previous models of RJVs that ignored factors such as complementarity of skills and resources of firms participating in an RJV were only partly valid. For example, these models predicted that cooperation would generally take the form of small firms in basic research, which has a relatively low probability of successful commercialization. In the presence of complementary skills and resources, however, we showed that successful cooperation was more likely and more desirable for firms when the technology is highly appropriable. Our model also indicated that large firms have potentially more ways to apply research results and thus gain from cooperation with industry rivals.

These general insights from the model also seem to explain reports of successful cooperative research in Japan: Most of the successful Japanese projects have focused on applied rather than basic research and were conducted primarily among large companies. There is thus a need to reexamine existing models of cooperative R&D as well as government policies that encourage RJVs mainly for basic research and among firms with relatively small market shares. These types of RJVs are not likely to succeed and do not seem particularly desirable for companies.

In general, an RJV should bring at least two key benefits to participants. First, the complementary skills and resources of participating firms may increase the probability of success in research. And second, the cost of R&D for participating firms should be reduced. But RJVs may create as many problems as they solve because firms face conflicting goals and difficulties in coordination. They also need to share any appropriable benefits of R&D with other participants. Our model suggests that large firms should have a large incentive to cooperate, given their greater potential benefits from the research, but they prefer small partners to limit how much they must share the venture's results. Small firms with the necessary skills, on the other hand, probably prefer to do their R&D alone. These contradictions make the ideal RJV among industry rivals difficult to achieve and probably account for much of the stress that accompanies RJVs in operation.

This analysis also indicates that cooperative R&D among industry rivals is not an ideal form of research partnership, precisely because of conflicting goals and incentives. The model thus confirms that firms are probably better off looking for partners in an RJV among universities, non-profit research institutions, or firms outside their industry. Nevertheless, as the Japanese cases demonstrate, RJVs among rivals may indeed prove successful if they are focused on applied technologies where individuals firms can foresee appropriable benefits from the research, divide tasks to reduce conflicts, and bring sufficient complementary skills and resources to the venture without comprising other company goals or competitive rivalries.

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Table 1

Japanese Cooperative R&D Projects in the Computer Industry

Period	Project/Organization (Total yen funding)	Objectives and Outcomes
Hardware Projects:		
1962-65	FONTAC Project (0.7 billion)	Led to the production of the first Japanese mainframe computer, the FACOM 230-50, though the introduction of IBM 360 in 1964 made it obsolete.
1966-68	Super High Performance (12 billion)	Developed the ICs and high speed memory necessary for larger and faster computers.
1972-76	New Series Project (N.A.)	Permitted Japanese companies to offer a full range of small to large mainframe computers.
1976-79	VLSI Project (72 billion)	Generated some 1,000 patents, helping move Japan into world leadership in the areas of 64K, 128K, and 256K semiconductors.
1979-87	Optoelectronics Project (18 billion)	Gave Japan a lead in the technology of optoelectronic ICs.
Software Projects:		
1966-72	Japan Software Company (2 billion)	Common development language and basic software for different architectures. Complete failure.
1970-82	IPA Package Effort (10 billion)	70 packages developed. Very limited usage.
1971-80	PIPS Project (22 billion)	Pattern-information (graphics) software, mainly for Japanese language processing. Several products commercialized. Links with Fifth Generation Project.
1973-76	Software Module Project (3 billion)	Applications development. Little coordination. Complete failure.

Period	Project/Organization (Total yen funding)	Objectives and Outcomes
1976-81	Production Technology Development Project (7.5 billion)	Initial goal of automatic code generation scaled down to the development of working aids for software programmers. The software tools failed to find a market.
1979-81	Next Generation Computer Technology Project (47 billion)	Helped develop Japanese language word processors.
1981-86	Software Maintenance Engineering Facility Project (5 billion)	Interactive, UNIX-based tool set for maintenance and development. Improved experience level of Japanese firms with UNIX.
1985-89	Interoperable Database System Project (1.5 billion)	Network to link work stations using OSI protocols. Improvement in interface standards likely.
1985-89	FASET Project (2.2 billion)	Development of CASE tools for automated code generation from formalized specifications. Limited participation.
1985-90	Software Industrialized Generator and Maintenance Aid (SIGMA) Project (25 billion)	Development of UNIX-based support tools as well as reusable code and packages, for a national network. Major dissemination of existing practical technology.
1982-91	Fifth Generation Project (50 billion)	Development of knowledge (logic-inference) processing and parallel computing hardware and software. Major long-term advances possible in Japanese AI capabilities. Short-term potential for software automation and reuse support. Limited commercial applications, however, and lukewarm support from major companies.

Note: All figures in current yen.
1 billion yen = Approximately $7 million in 1989.

Sources: Anchordoguy (1989) and Cusumano (1990).

FIGURE 1

Four Types of Reseach Joint Ventures