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Multi-task Research and Research Joint Ventures

Abstract: The paper shows that, whenever the completion of a research project requires the overcoming of *more than one* research obstacle, then Research Joint Ventures enjoy an intrinsic advantage relative to independent firms. This advantage, which has hitherto escaped attention in the RJV literature, relates to the RJV's ability to *organize* research more efficiently than independent firms. The fact that RJVs can be both more profitable and yield higher expected net welfare than independent firms is surprising because it is derived from a model in which RJVs do *not* optimize over R&D investment. The paper exploits a basic result in systems reliability theory to establish the organizational superiority of RJVs.

JEL Numbers: L1, O3
Keywords: research joint ventures, spillovers, organization of R&D, multi-task research, multi-path research, systems reliability theory

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1 Introduction

The large amount of literature on Research Joint Ventures (RJVs) that has accumulated in the last 20 years or so[1] is based on the assumption that the process whereby new useful ideas are discovered (the innovation process) can be largely "black boxed" with no significant loss to the robustness of the resulting analysis of the links between the research process and the formation, organization, and performance of RJVs. This paper questions this underlying assumption and suggests that even a basic understanding of the information flows involved in the production of innovations can not only provide useful insights into RJVs, but also add a new set of features to be taken into account when assessing the desirability (or otherwise) of RJVs.

1 Recent surveys include Caloghirou *et al.* (2003), Sena (2004), Silipo (2003).

Before peering into the black box of innovation, it may be useful to advance a possible explanation as to why most models of collaborative research tend to neglect the specific nature of process whereby new ideas are produced.

The theoretical literature on RJVs was initially developed as an application of multi-stage games to the increasingly policy-relevant field of inter-firm collaboration in R&D. The emphasis was on the optimal *allocation* of resources to R&D under alternative competitive/cooperative regimes in each of the *strategic* stages of the game (typically, some combination of choice of R&D investment, of R&D collaboration, and of output/price levels). The ultimate aim of the literature has been to identify the mix of type of research collaboration and of competitiveness in each stage of the game yielding the highest welfare. This modeling strategy has been remarkably successful in so far as it has produced very helpful insights on the delicate interplay of R&D investment, collaborative research, and final-output market outcomes, without having to specify how the distinctive features of research may affect the behavior of RJVs.

This paper considers the effects on RJVs of two defining characteristics of research:

(i) the successful completion of almost any research project involves the overcoming of *more than one obstacle* (the *multi-task* nature of research); and
(ii) typically there is *more than one way* to overcome any given research obstacle (the *multi-path* nature of research).[2]

The paper attempts to show that the resulting marginally less coarse description of the research process has first-order effects on the efficiency of RJVs.

The central idea of the paper is very simple and can be summarized as follows. Consider a $2 \times 2 \times 2$ world where an invention can be obtained only if *two* research tasks (task A and task B) are completed successfully and where there are *two* possible methods of accomplishing each task. Each of two firms decides independently which method to try for each task. Therefore it is perfectly conceivable that if firms choose different methods, one firm can succeed in task A and fail in task B, whereas its rival fails in task A and succeeds in task B. As a result, neither firm manages to produce the invention. Suppose now that the two firms carry out *exactly the same* research plan, but form a RJV whereby information about *each* task is shared. Obviously, by combining firm 1's successful method for task A with firm 2's success in task B, the RJV achieves the overall success that could not be obtained by each firm independently.

2 Obviously, neither of the above characteristics of the research process would matter if the outcomes of projects were non-stochastic and thus in what follows it will be assumed that success in research is uncertain.

Before presenting the model, a warning must be issued to readers familiar with the current literature on RJVs: the modeling strategy adopted in this paper is a *complete reversal* compared to most existing models of RJVs. The latter determine the efficiency of RJVs in terms of the *volume* of R&D investment (or cost reduction/product improvement), whereas the present paper shows that even for a *fixed and sub-optimal* level of R&D inputs, RJVs may yield a welfare improvement relative to independent research. Indeed the paper biases the analysis heavily against RJVs vis-à-vis independent research, by assuming that independent firms do optimize over the volume of R&D investment, but RJVs *do not*. In spite of this handicap, the paper highlights the existence of a hitherto neglected but potentially large *organizational surplus*, i.e., an unambiguous Pareto improvement that can be achieved by firms forming an RJV even though their R&D investment is constrained to a sub-optimal level. In other words, in this paper one of the major advantages of RJVs highlighted in the literature, namely, that RJVs can avoid duplication of research efforts, is removed by construction, thereby making the analysis biased *against* RJVs.

2 A simple model of multi-task research projects

Although unfamiliar to most economists, the field of systems reliability[3] provides a very useful analogy for the modeling of multi-task, multi-path, non-deterministic research.

The diagram described in Figure 1, familiar to any electrical/electronic engineer, shows a simple structure where each dot represents a "switch", i.e., the most elementary example of a device that can either work or fail. In this particular instance, the five switches are connected in such a way that the whole structure can function (i.e., a connection from I to K can be established) even if not all five switches work. Indeed there are four different ways in which this structure can perform, namely, when any of the four "routes" $\{x_1, x_2\}$, $\{x_4, x_5\}$, $\{x_1, x_3, x_5\}$, $\{x_4, x_3, x_2\}$ is working.

The very same structure can be interpreted in terms of a research problem, whereby in order to achieve a "discovery", i.e., to move from Ignorance to

3 The seminal paper in this area is "Probabilistic logics" (1956) where John von Neumann (who else?) showed how to combine unreliable devices (the so-called "Sheffer stroke") so that they can function as a system of higher reliability.

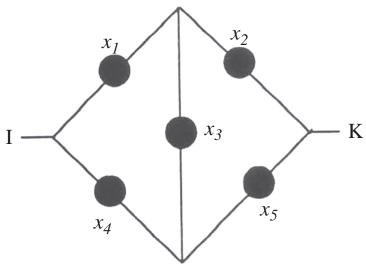

Figure 1: A multi-component system – the “bridge” structure.

Knowledge, there is essentially a pair of two-obstacle search routes (namely $\{x_1, x_2\}$ and $\{x_4, x_5\}$) with an additional “bridging” route (x_3).[4]

The basic notion underlying this paper is that there exists a very close relationship between the way the process of research is structured and the way in which a multi-component system can be organized. With reference to the research problem described in Figure 1, each “dot” represents a “research unit” (laboratory, R&D personnel, etc.) assigned to a specific task. The structure of the problem to be solved is fully captured by the way in which the research units are connected and can be described as follows: there are two substantive research obstacles to be overcome, each of which can be tackled in two different ways. One obstacle can be surmounted by the successful accomplishment of either task x_1 or task x_4, while the removal of the other obstacle requires the completion of either task x_2 or task x_5, with task x_3 acting as a “translator”, i.e. making the outcome of task x_4 (respectively, x_1) available to task x_2 (respectively, x_5).

This is hardly surprising: anyone engaged in research is only too painfully aware that, typically, the attainment of any research goal involves the overcoming of more than a single obstacle and that usually there is more than one way of tackling any given obstacle.

As this is, to the best of my knowledge, the first attempt to model research as a multi-component structure, I may be forgiven for concentrating on this aspect of the innovation process, ignoring other important features of research, e.g., its sequential nature.[5] This implies that the *order* in which tasks are

4 To mention an example familiar to the reader, suppose that the aim is to write a publishable paper in mathematical economics where the first “obstacle” may be proving an existence theorem (which can be established either by topological means (x_1) or constructively)** (x_4) and the second obstacle may be proving a uniqueness theorem (which, again, can be done topologically)** (x_2) or constructively (x_5), with (x_3) being a way of translating a topological story into a constructive argument.

tackled is immaterial. In order words, the results examined in the paper apply to any sort of modular[6] research problem, defined as a problem where the probabilities of success in each tasks are statistically and temporally independent.

Three examples may suffice to suggest that modularity is a significant feature of many innovation processes.

Baldwin and Clark (2000) have devoted an entire book to showing how the major breakthrough in the efficient production of personal computers came about with the decision by IBM in the early 1960s to produce the System/360 in an explicitly modular fashion, setting up independent teams working on separate problems thanks to an overall product architecture that allowed product designers to combine individual components into an organic whole with a minimum of inter-component "interference".

Another example of planned modularity is provided by Rolls-Royce's major commercial success of the RB211 family of jet engines, whereby the traditional two-shaft engine was replaced by a three-shaft model, which by splitting the compression work across three independent compressors (one each for low-, medium-, and high-compression) with their own turbines, not only has allowed the RB211 family to improve engine performance dramatically, but also has provided a design that can be adapted to individual customer needs much more efficiently simply by tweaking the characteristics of individual compressors.

A topical example of modularity is provided by the accelerated development of an H1N1 vaccine (against "swine flu"), with the manufacturer being reported as working simultaneously at researching new ways of increasing the volume of production and at the proportion of active ingredients in the vaccine.

5 As modelled, for example, in Weitzman (1979) and Weitzman and Roberts (1981).

6 My use if the term *modular* is related to, but different from, two standard uses: in mathematical economics a function $f(\bullet)$, which, for simplicity we can assume smooth, is modular if $\frac{\partial^2 f}{\partial x_i \partial x_j} = 0$ for $\forall i \neq j$ (see the classic treatment in Topkis (1998)). In management science, and especially in product design, the notion of modularity is similar to Simon's concept of decomposable systems, meaning the extent to which large complex problems can be broken down into smaller sub-problems. The connection between the two concepts is that if the interactions between variables/subsets are weak or non-existent, then the search for optimal solutions can be achieved in a piece-meal fashion (see Brusoni *et al.* (2007) for an example and algorithm).

3 Multi-task multi-path research by independent firms

In order to separate the familiar analysis of the optimal *allocation* of research resources from a novel approach to the optimal *organization* of research, first I provide a very general formulation of the former, as follows.

In an industry populated by N independent firms (for my purposes it is immaterial whether N is exogenously fixed or is determined by a free entry condition) a typical firm i chooses its R&D effort x_i so to solve the following program:

$$\max_{x_i}\left[G_i\left(\sigma_i(p_i(x_i,x_{-i}))\right)-C_i(x_i,x_{-i})\right];\, i=1,\ldots,N, \text{ where} \quad [1]$$

$G_i(\cdot)$ = firm i's gross profit function,
$\sigma_i(\cdot)$ = firm i's probability of *system* success
$p_i(\cdot)$ = firm i's probability of *component* success
$C_i(\cdot)$ = firm i's total cost of R&D
$x_{-i} \equiv x_1,\ldots,x_{i-1},x_{i+1},\ldots,x_N$

Notice that the above formulation allows for extensive information spillovers, in so far as the vector x_{-i} enters both the probability of success function and the total cost of R&D function.

Notice also that in a multi-task research process a distinction must be drawn between *system* and *component* success, the former being the probability that *all* research tasks are accomplished; the latter being the probability that a single task is completed successfully.

Obviously in order for a meaningful comparison to be made between independent research and a research joint venture, it must be assumed that the former attains a stable unique equilibrium. For the remainder of this paper it is assumed that $G_i(\cdot)$, $\sigma_i(\cdot)$, $p_i(\cdot)$, and $C_i(\cdot)$ are well behaved in the sense that the program eq. [1] yields a unique symmetric Nash equilibrium whereby each independent firm invests x^I in R&D effort. To save on notation the following shorthand is used: $p \equiv p(x^I, x^I_{-i})$, i.e., henceforth the probability of component success p refers to the Nash equilibrium value for N independent firms.

Having established the benchmark for the optimal allocation of R&D efforts under independent research, we can address the issue of the optimal organization of research.

In order to produce an invention, each firm has to solve T "research tasks", each of which can be solved through M distinct methods, $(m_1,\ldots,m_M)$, with probability of (component) success $(p^1,\ldots,p^M)$.[7] For simplicity it is assumed that $p^1=\ldots=p^M=p$, i.e., for a given amount of R&D investment all methods are equally probable to succeed, but all the results in the paper apply also to the non-symmetric case.[8] To avoid uninteresting complications we assume that the total number of potential methods is large enough that we can ignore the case where more than one firm tries the same method for any given task and therefore the number of methods that can be tried for any given task is given by the number of firms N engaged in research.[9] The simplest interpretation of this stochastic process is when each firm follows a different research path.[10] In this simplest of models of multi-task research the Nash equilibrium value of per-firm expected gross profits can be computed as follows:

$$G(p)=\sum_{i=1}^{N}\binom{N-1}{i-1}(p^T)^i(1-p^T)^{N-i}\frac{\pi_M}{\alpha_i} \qquad [2]$$

It may be noted that the above is a very general formulation that encompasses both *tournament* and *non-tournament* models of technological competition, to use the distinction introduced by Dasgupta (1986).

In a tournament game, firms compete for a single prize π_M (e.g., the present value of the stream of monopoly profits generated by a single patent) and, in the event of i firms succeeding ($i>1$), each of the i successful firms has a probability $\frac{1}{i}$ of reaping monopoly profits. Thus in eq. [2] $\alpha_i=i$.

In a non-tournament game, the payoffs from successful innovation depend on market structure in the following sense: if only one firm (j firms) succeeds (succeed) at the research stage it (each) collects profits (gross of research costs) $\pi_i\equiv\frac{\pi_M}{\alpha_i}, i=1,\ldots N$, where π_M is monopoly profits and α_i is an index of market competition.

7 Here superscripts refer to tasks, not to firms.

8 By making this symmetry assumption we are ignoring some interesting applications of the "systems reliability" approach to research organization, in so far as the approach sketched here yields some sharp implications on the optimal assignment of R&D resources when tasks are not equally difficult to accomplish.

9 Notice that this assumption biases the analysis *against* RJVs in so far as an RJV would never try the same method more than once and therefore could achieve a resource saving with no decrease in the overall probability of success compared to independent firms following identical methods.

10 As mentioned later, the model also applies to the case where only one method succeeds (with certainty), but it is not distinguishable *ex ante* from the other M–1 useless methods, so that *ex ante* $P^{\mathrm{I}}=\ldots=p^M=\frac{1}{M}$.

In other words, in a non-tournament model, as there are multiple prizes and therefore profits are dissipated through (imperfect) competition, the αs will satisfy the following restrictions:

$$\alpha_1 = 1, \frac{i\pi_M}{\alpha_i} > \frac{(i+1)\pi_M}{\alpha_{i+1}}, \forall i > 1, \qquad [3]$$

i.e., gross *industry* profits must be decreasing in the number of active firms. For example, in the textbook case of a linear Cournot oligopoly (i.e., when output-setting firms operate under a linear demand curve $p(Q) = A - Q$ with constant marginal costs normalized to zero), it can be easily computed that: $\pi_M = \frac{A^2}{4}, \alpha_1 = 1, \alpha_2 = \frac{9}{4}, \alpha_3 = 4, \alpha_4 = \frac{25}{4}$, etc.

4 Multi-task multi-path research by organization-efficient RJVs

As the issue of the optimal organization of RJVs under multi-task, multi-path research has not been addressed in the literature it may be useful to introduce the concept of *organizationally efficient* RJV.

Recall that an invention can be produced only if all T tasks are completed, with each task having M possible methods of accomplishing it. As with the case of independent research, we assume w.l.o.g. that each firm can try only one method for each task.

If N firms wish to pool their **fixed** resources to maximize the probability of overall success, how should research be organized? The answer to this question is found by comparing two dual organization structures:

(i) N teams are formed, with each team picking one possible method for each of the T tasks and testing the resulting combined overall solution.[11] The probability of system success, when each task has the same probability of success p is easily computed as $\sigma^{N\text{teams}}(p) = 1 - \left(1 - p^T\right)^N$

(ii) T teams are formed (one per task), each team using N possible methods to accomplish the assigned task.[12] The probability of system success now is given by $\sigma^{T\text{teams}}(p) = \left(1 - (1-p)^N\right)^T$.

11 In systems reliability terminology this is a *parallel-series* arrangement, whereby N series of T components each are arranged in parallel.

12 This is a *series-parallel* arrangement whereby T arrangements of N components are each arranged in series.

Notice that the overall number of methods deployed to solve the overall problem (i.e., *NT*) is the same for the two organization structures.

A key result in systems reliability theory states that:

Theorem 1 (after Ross(1996)):

For any $1 > p > 0$, $\sigma^{T\text{teams}}(p) \equiv \left(1-(1-p)^N\right)^T > 1-(1-p^T)^N \equiv \sigma^{N\text{teams}}(p)$.

Proof: see Appendix.

Theorem 1 is crucial to the understanding of the built-in *organizational* efficiency of RJVs: if an RJV can choose its organizational structure (as we assume here, unlike most of the literature on RJVs), it will always select to duplicate effort for each task, and not to replicate whole research teams (when each team attempts to accomplish all tasks).

We are now in a position to compare independent research with an organizationally efficient RJV.

For most of the analysis, attention will be restricted to the simple case of *industry-wide* RJVs, namely where the only alternative to independent research is for *all* firms in the industry to join a single RJV. In this case we can restrict the analysis to *two* firms as the extension to $N > 2$ is conceptually straightforward and notation-wise cumbersome. In the last section, a brief example will be provided of a *partial* RJV (i.e., when a proper subset of firms join a RJV, while others remain independent) showing that the qualitative results obtained in the case of industry-wide RJVs are likely to apply more generally.

5 Independent firms vs organization-efficient RJVs

In order to obtain a given innovation any given firm has to complete *T* research tasks, and w.l.o.g. we can assume that each firm can try only one method for each of the *T* tasks, each of which has a probability of success *p*. Thus the probability of overall success for an independent firm is p^T and its expected gross profit is given by:

$$G^I \equiv \sum_{i=1}^{N} \binom{N-1}{i-1} \left(p^T\right)^i \left(1-p^T\right)^{N-i} \frac{\pi_M}{\alpha_i}. \qquad [4]$$

i.e., for an independent firm, its expected gross profit is a weighted average of all possible profits, starting with monopoly profits (π_M) when all other competitors fail and ending with the lowest profits ($\frac{\pi}{\alpha_N}$), when all its competitors also succeed.

Expected gross profit for a member of an N-firm organization-efficient RJV is given by:

$$G^{\mathrm{RJV}} \equiv \left[1-(1-p)^N\right]^T \frac{\pi}{\alpha_N}. \tag{5}$$

i.e., provided the organization-efficient RJV succeeds (which happens with probability $[1-(1-p)^N]^T$), all RJV members will compete in the final output market and collect the lowest possible profits $\frac{\pi}{\alpha_N}$.

I examine first the case of a tournament model, which turns out to yield a strong unambiguous result:

Proposition 1. For $\forall T \geq 2, \forall N \geq 2$, *if firms compete for a single prize, membership of an organization-efficient RJV is* ***always*** *more profitable than independent research.*

Proof:

Expected gross profits for an independent firm are given by:

$$G^I \equiv \sum_{i=1}^{N} \binom{N-1}{i-1} \left(p^T\right)^i \left(1-p^T\right)^{N-i} \frac{\pi_M}{i} \tag{6}$$

which can be rearranged as:

$$G^I \equiv \sum_{i=1}^{N} \binom{N}{i} \frac{i}{N} \left(p^T\right)^i \left(1-p^T\right)^{N-i} \frac{\pi_M}{i} = \left[1-(1-p^T)^N\right] \frac{\pi_M}{N}. \tag{7}$$

The proposition follows from Theorem 1:

$$G^I \equiv \left[1-(1-p^T)^N\right] \frac{\pi_M}{N} < \left[1-(1-p)^N\right]^T \frac{\pi_M}{N} \equiv G^{\mathrm{RJV}}. \tag{8}$$

Proposition 1 is remarkably general, as it holds for any maximization program that guarantees a unique Nash equilibrium for independent firms (recall that in the above computations $p \equiv p(x^I, x^I_{-i})$, where $\mathbf{x}^I$ the *equilibrium* investment in R&D by independent firms), and for any multi-task ($T \geq 2$) research project and for any number of firms $N \geq 2$.

It is interesting to see why the above inequality holds. The first term of the per-firm gross profit from independent research, $[1-(1-p^T)^N]$, turns out to be the overall probability of success that would be achieved by a RJV if it was organized *inefficiently*, i.e., if each of N teams tackled all T tasks. In other words, Proposition 1 establishes that for a single-prize tournament the payoff for an individual firm carrying out independent research is the same as for a member of a N-firm RJV organized *inefficiently*.

In the Appendix a simple example shows how the superiority of an efficiently-organized RJV extends to the more general asymmetric case (when the probabilities of success vary across tasks) and a more general model of information flows is provided that generates independent research and fully efficient RJVs as special cases.

In the non-tournament case, two opposing forces are at work. On the one hand, the greater probability of overall success under an organization-efficient RJV established for the tournament model still holds. On the other hand, in the non-tournament scenario the gross profit earned by each member of the RJV could be so small as to nullify the RJV's organizational advantage. To take an extreme example, suppose that for $\forall N \geq 2, \alpha_N = \infty$ (as would be the case in a constant-marginal cost homogeneous-good Bertrand oligopoly). Then no RJV could break even. Given that no unambiguous results like Proposition 1 can be established for the non-tournament case, it is more revealing to focus on specific examples that bring out the tension between these two opposing forces.

I consider first the two-firm case. Expected gross profits for independent firms and for members of the organization-efficient RJV are given by:

$$G^I \equiv p^T \left[(1-p^T)\pi_M + p^T \frac{\pi_M}{\alpha_2} \right] \qquad [9]$$

$$G^{\text{RJV}} \equiv p^T (2-p)^T \frac{\pi_M}{\alpha_2} \qquad [10]$$

Proposition 2. If two firms compete for a monopoly prize π_M and a duopoly prize $\frac{\pi_M}{\alpha_2}$, then membership of an organization-efficient RJV is more profitable than independent research for all values of T, p, and α_2 such that

$$\alpha_2 < \frac{(2-p)^T - p^T}{1-p^T}. \qquad [11]$$

Figure 2 shows the range of (p, α_2) values for $T = 2,3$ such that the RJV dominates independent research (recall that $\alpha_2 > 2$, otherwise duopoly profits would exceed monopoly profits!).

Recall that for a constant-marginal cost linear Cournot oligopoly, $\alpha_2 = 2.25$, so that an efficiently-organized RJV is more profitable than independent research for $p < \frac{7}{9}$ in the two-task case, $p \leq 0.888$ in the three-task case, etc.

It is simple to show that the superiority of RJVs increases with the complexity of research (i.e. with the number of tasks T)[13] and with the difficulty of individual tasks (i.e., with $(1-p)(1-p)$).

13 $\dfrac{d\,\frac{(2-p)^T - p^T}{1-p^T}}{dT} > 0$

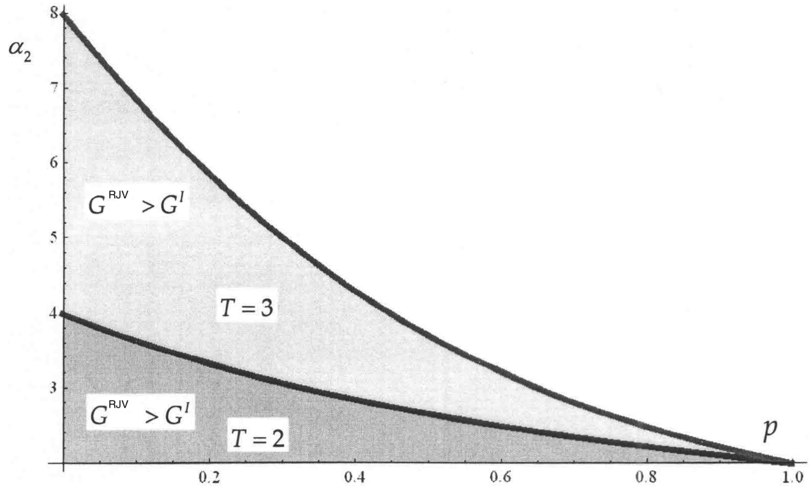

Figure 2: When is a 2-firm RJV superior to independent research?

To complete the two-firm case we may consider a different stochastic process, namely, the scenario where for each task only one out of M possible methods yields success, with the remaining $M-1$ being "dry holes". If two tasks have to be completed, the probability of overall success for an independent firm and for a member of the organization-efficient RJV are given respectively by $\left(\frac{1}{M}\right)^T$ and $\left(\frac{2}{M}\right)^T$. The reason why in this case an RJV is 2^T times more likely than an independent firm to succeed in completing all T tasks is that this case provides an extreme example of an intrinsic advantage of RJVs that is ignored elsewhere in the paper, namely, RJVs can co-ordinate the type of solutions being attempted to solve each task and thus avoid the possible duplication of efforts that occurs under independent, unco-ordinated research. Substituting the above probabilities in eq. [11] we obtain:

Proposition 2'. If two firms compete for a monopoly prize π_M and a duopoly prize $\frac{\pi_M}{\alpha_2}$, then membership of an organization-efficient RJV using two out of M possible methods per task is more profitable than independent research for all values of T, M, and α_2 such that

$$\alpha_2 < \frac{2^T - \left(\frac{1}{M}\right)^T}{1 - \left(\frac{1}{M}\right)^T}. \qquad [11']$$

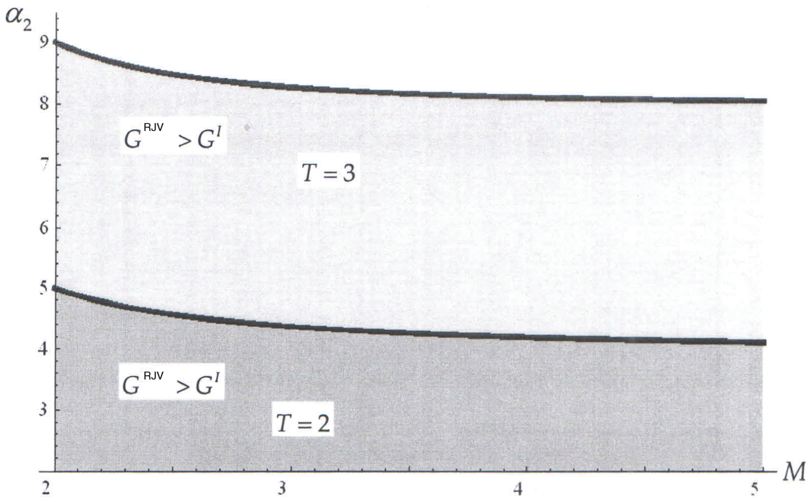

Figure 3: When is a 2-firm RJV superior to independent research (with minor research coordination)?

As it can be seen from Figure 3, where the shaded areas indicate the values of *M* and α_2 that satisfy condition eq. [11'] for $T = 2,3$, organizational advantage of the RJV far outweighs the competitive disadvantage of foregoing the prospect of earning very large monopoly profits (compared to duopoly profits).

Even though the full analysis of the case of $N > 2$ firms is a matter for future research, the following section suggests that the organizational superiority of RJVs is not confined to the two-firm case.

6 Full and partial RJVs in a cournot triopoly

The expected gross profits per firm under independent research in a 3-firm linear Cournot oligopoly with *T* research tasks are given by:

$$G^I = p^T\left[(1-p^T)^2\pi_M + 2(1-p^T)p^T\pi_M\frac{4}{9} + (p^T)^2\pi_M\frac{1}{4}\right] \tag{12}$$

whereas each member of the 3-firm organization efficient RJV earns gross profits of:

$$G^{\mathrm{RJV}} = \left[1-(1-p)^3\right]^T\pi_M\frac{1}{4} \tag{13}$$

Solving the polynomial $G^I(p) = G^{\mathrm{RJV}}(p)$ shows that in the linear Cournot triopoly case the organization-efficient *full* RJV (when all three firms join) is more

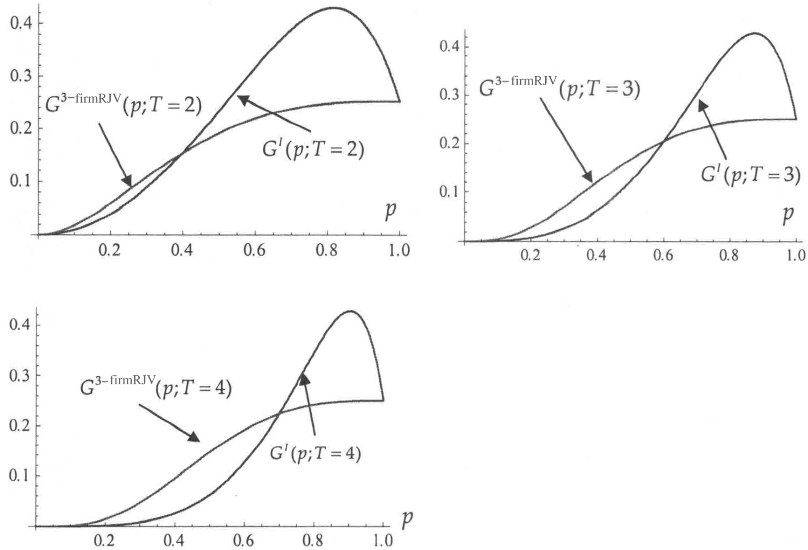

Figure 4: When is a 3-firm RJV superior to independent research?

profitable than independent research for any value of p less than a critical cut-off $\overline{\overline{\overline{p}}} = 0.397$ (for $T = 2$), $\overline{\overline{\overline{p}}} = 0.6$ ($T = 3$), $\overline{\overline{\overline{p}}} = 0.69$ ($T = 4$) (Figure 4).

Of course, for $N > 2$ we have to consider the case of *partial* RJVs, i.e., research collaboration between fewer than the total number of firms in the industry. In the case of a triopoly this means introducing two additional gross profit functions, the per-member gross profits for a 2-firm RJV:

$$G^{2-\text{firmRJV}} = \left[1-(1-p)^2\right]^T \left\{(1-p^T)\pi_M \frac{4}{9} + p^T \pi_M \frac{1}{4}\right\} \qquad [14]$$

and the gross profits of the "solitary" firm excluded from the RJV:

$$G^S = p^T \left\{\left(1-\left[1-(1-p)^2\right]^T\right)\pi_M + \left[1-(1-p)^2\right]^T \pi_M \frac{1}{4}\right\} \qquad [15]$$

This simple example enables us to establish that a partial RJV may not be a stable configuration, i.e., it is not coalition-proof.

For a partial RJV not to be coalition-proof, two conditions must hold: (i) the excluded firm must find profitable bribing each member of the 2-firm RJV, and (ii) each member of the 2-firm RJV must be better off by accepting the bribe $\frac{b}{2}$, i.e.,

(i) $G^{3-\text{firmRJV}} - b > G^S$ and [16]

(ii) $G^{3-\text{firmRJV}} + \dfrac{b}{2} > G^{2-\text{firmRJV}}$, i.e., [17]

$3 \times G^{3-\text{firmRJV}} > 2 \times G^{2-\text{firmRJV}} + G^S$ [18]

Solving the relevant polynomial shows that inequality eq. [18] holds for all p less than a critical cut-off $\overline{\overline{p}} = 0.444$ (for $T = 2$), $\overline{\overline{p}} = 0.636$ (for $T = 3$), and $\overline{\overline{p}} = 0.715$ (for $T = 4$). It follows that, as $\overline{\overline{p}} > \overline{\overline{\overline{p}}}$, the unique coalition-proof configuration is either a full (3-firm) RJV (for $\forall p < \overline{\overline{\overline{p}}}$) or independent research by all three firms (for $\forall p > \overline{\overline{\overline{p}}}$).

7 Conclusions

In this paper, research joint ventures not only have been stripped of all the potential advantages highlighted in the literature, e.g., avoidance of duplication, possibility to co-ordinate research activities, etc., but most acutely of all have been prevented, by design, from allocating resources to R&D efforts in an optimizing way. In spite of these crippling handicaps, it has been shown that for a very wide range of market structures (summarized by the α_i parameters) RJVs can be more profitable and yields higher levels of net expected social welfare than independent research, provided they choose the most efficient *organization* of resources.

The simple model sketched in this paper can be extended in various directions, but I shall mention just two. First, in a richer model RJVs should optimize over *both* the allocation *and* the organization of R&D resources. This is unlikely to be a purely "additive" process, because the optimal organization of research may interact in non-obvious ways with optimization over resource allocation. Second, the organizational aspects of RJVs can be extended to cover research design: for example, an RJV can select a method to solve a particular task with a lower probability of success than an alternative method, if the former is more "generic", i.e., more likely to be combined successfully with solutions to other tasks. The development of the theory of fully optimizing RJVs appears to be both feasible and rich with valuable insights.

Appendix

A1 Proof of Theorem 1

The basic result that a series of parallel arrangements of components is more likely to succeed than a parallel arrangement of series of components has a status akin to the Folk Theorem in game theory and is similarly tricky to pin down to a definite source. Perhaps the simplest version can be found in Ross (1996, Theorem 9.1) which can be adapted to prove Theorem 1 in the paper as follows:

Theorem 1 (after Ross (1996)):

For any $1 > p > 0$, $\sigma^{T\text{teams}}(p) \equiv \left(1-(1-p)^N\right)^T > 1-(1-p^T)^N \equiv \sigma^{N\text{teams}}(p)$.

The above theorem is both a special case and a trivial extension of Theorem 9.1 in Ross (1996).

For any $S(.)$ *and T-dimensional vectors* $\mathbf{p}$, $\mathbf{p}'$: $s[\mathbf{1}-(\mathbf{1}-\mathbf{p})(\mathbf{1}-\mathbf{p}')] > 1-[1-s(\mathbf{p})][1-s(\mathbf{p}')]$, *where* $s(\mathbf{p})$ *is the probability that a series of T components with individual probability of success* $\boldsymbol{p}$ *succeeds.*

Theorem 1 follows from the above by setting $\mathbf{p} = \mathbf{p}'$ and by iterating Theorem 9.1 N times (and not just twice as in Theorem 9.1).

A2 The bridge structure as a general model of information flows

Consider the "bridge" structure depicted earlier in Figure 1 and assume that the probabilities of individual task success for firms A and B are respectively p_A and p_B, as in Figure 5. Moreover, for reasons that will become apparent shortly, introduce a "connecting" unit that succeeds with probability κ.

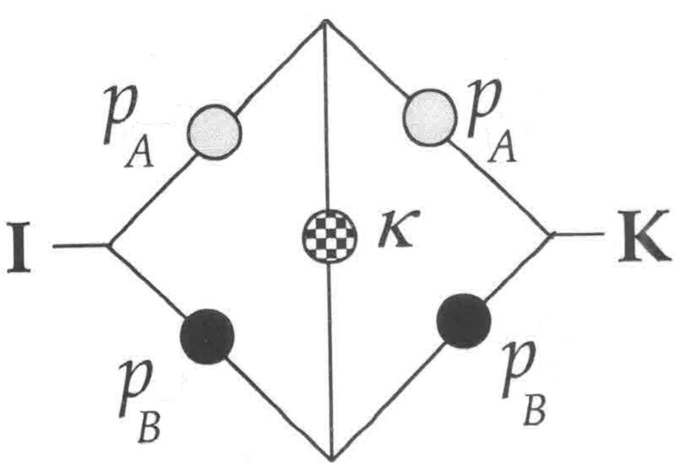

Figure 5: The bridge structure and information flows.

It is straightforward to compute the overall probability of success of the "bridge" structure, $\sigma^B(p_A, p_B, \kappa)$, as:

$$\begin{aligned}\sigma(p_A, p_B, \kappa) = {} & p_A{}^2 p_B{}^2 + 2p_A{}^2 p_B(1-p_B) + 2p_B{}^2 p_A(1-p_A) + \\ & p_A{}^2(1-p_B)^2 + (1-p_A)^2 p_B{}^2 + 2\kappa p_A(1-p_A)p_B(1-p_B)\end{aligned} \qquad [19]$$

Notice that under symmetry ($p_A = p_B = p$) eq. [19] simplifies to:

$$\sigma(p, \kappa) = p^2\left[2 - p^2 + 2\kappa(1-p)^2\right] \qquad [20]$$

Equation [20] shows that the "bridge" structure encompasses both types of RJV organizations (inefficient, with *N* teams; efficient, with *T* teams) as special cases:

$$\sigma^B(p, 0) = p^2\left[2 - p^2\right] \equiv \sigma^{N\text{teams}} \qquad [21]$$

$$\sigma^B(p, 1) = p^2(2-p)^2 \equiv \sigma^{T\text{teams}} \qquad [22]$$

This observation is interesting for three reasons: (i) the organization-efficient RJV, by assigning a team to each task, effectively introduces additional information flows across tasks, which explains why it dominates the alternative arrangement (assigning each team to the full series of tasks); (ii) even when inter-task information flows are imperfect (i.e., $0 < \kappa < 1$), organization-efficient RJVs are more likely to achieve overall success than independent firms; (iii) the superiority of efficient RJVs may hold also in the case (not examined in this paper) when the probabilities of individual success are not statistically independent.

Using eq. [19] we can get an insight into the quantitative superiority of RJVs compared to independent research. Recalling that in a tournament model the profits from independent research are the same as from membership of an *inefficient* RJV, we can compute the rate of return from forming an *efficient* RJV as:

$$\rho(p_A, p_B) = \frac{\sigma^B(p_A, p_B, 1) - \sigma^B(p_A, p_B, 0)}{\sigma^B(p_A, p_B, 0)}. \qquad [23]$$

Figure 6 shows that, for the relevant case when success in individual tasks is "difficult" (i.e., $p_X \le 0.5$), this rate of return ranges from nearly 100% to 10%:

The formulation of the alternative organizational structures open to an RJV in terms of the "bridge structure" provides a simple way of comparing the results in this paper with the vast literature on RJVs spawned by d'Aspremont and Jacquemin (1988) and Kamien *et al.* (1992). A distinctive feature of this literature is to regard the formation of an RJV as a means of endogenizing any spillover

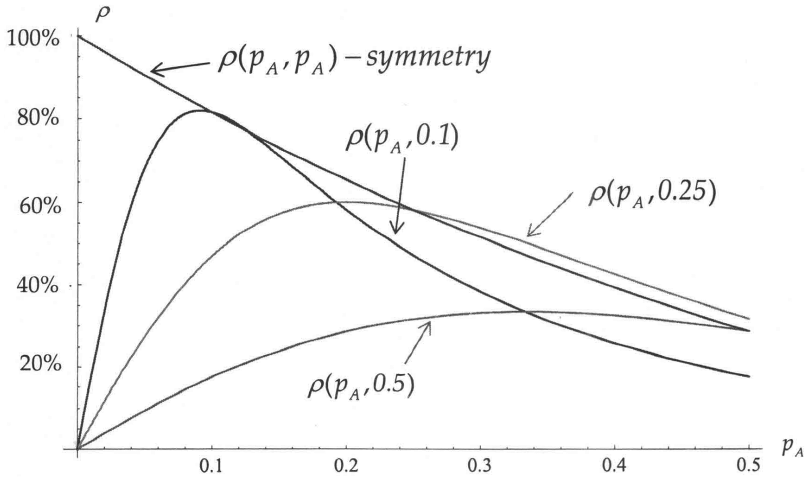

Figure 6: Rate of return for efficient RJVs.

effect. For single-task research, this effectively amounts to assuming that any RJV member agrees to share its successful innovation with all other members. Under multi-task research there is a richer network of potential information flows, some of which can be formalized by means of our bridge structure. The canonical RJV model, where members share information about completed *projects* is captured by setting $\kappa = 0$ in eq. [19], whereas an organizationally-efficient RJV would share information about completed *tasks,* i.e., would set $\kappa = 1$. Notice also that the bridge structure can be used to model the case where different research tasks undertaken by different RJV members may not be fully compatible, i.e., success in task *i* by member A when combined with success in task *j* by member B leads to the whole project succeeding with probability $\kappa < 1$.

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