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Organizational design of R&D activities

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Abstract

This paper addresses the question of whether R&D should be carried out by an independent research unit or be produced in-house by the firm marketing the innovation. We define two organizational structures. In an integrated structure, the firm that markets the innovation also carries out and finances research leading to the innovation. In an independent structure, the firm that markets the innovation buys it from an independent research unit which is financed externally. We compare the two structures under the assumption that the research unit has some private information about the real cost of developing the new product. When development costs are negatively correlated with revenues from the innovation, the integrated structure dominates. The independent structure dominates in the opposite case.

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1 Introduction

Research and development activities take place in various organizational forms depending on who finances, creates, develops, produces and sells the innovation. A widely observed organizational form is in-house R&D. The innovation is financed and produced within the same firm who uses the new product or the new technology. Researchers-inventors are subject to an employment contract.

Innovations can also be produced externally. Research and development activities are conducted by an independent firm whose objective is to create a new product or a new technology and then to develop it in a venture with the user firm. The innovation process is managed and owned by the independent research unit firm and financed by a financial partner, for example, a venture capitalist.

Both organizational structures are observed in many industries. In the pharmaceutical industry, a firm like Merck finances mainly in-house R&D, while some of its major rivals are outsourcing most of their research activities to biotechnology firms. Only 5% or so of Merck's research spending ends up outside the firm's laboratories. For other top drug companies, however, the proportion of research done externally can reach 80%. Recently, some American pharmaceutical companies moved from in-house R&D to independent R&D by increasing their research joint-venture agreements. These research joint ventures are contractual agreements for developing, producing and selling a new medicine discovered by a biotech firm (Lerner and Merges, 1998). In 1994, 117 ventures between drug and biotechnology firms were signed, 70% more than the previous year.[1]

This empirical evidence raises an important question. Why are different organizational forms observed? If one organization is more efficient than the other one, the inefficient organizational structure should not be observed, or should disappear in the long run. The objective of this paper is to provide arguments based on contractual imperfections that explain the choice of an organizational structure for R&D activities.

[1] *"The Economist"*, May 13th 1995, pp. 66–67, and May 24th 1997, pp. 59–60.

The economic environment for research and development activities and the eventual marketing of the innovation is characterized by two main features: uncertainty and informational asymmetries. When working on an innovation, a firm does not know for sure the result of its R&D activities. Research methodologies employed to discover an innovation (what Dosi (1988) calls "technology trajectories") can be specified ex ante but their outcome can hardly be perfectly predicted. For example, in the case of the pharmaceutical industry, one favorite research methodology employed is "combinatorial chemistry" which consists in using arbitrary chemical reactions to generate millions of randomly shaped molecules. One of the new discovered molecules might just lead to the next drug. The discovery of a new drug depends on the success of this process, and its properties such as safety, efficiency, cost effectiveness of treatment are never known ex ante. Research and development activities are random and, therefore, constitute a risky investment.

Second, the marketing of an innovation is characterized by asymmetric information. The value of an innovation depends on characteristics such as the new technology's efficiency or the new product's quality. While this information is difficult to obtain before the innovation is developed, produced and sold, the research unit may have more information about the cost of bringing the innovation to the market. For example, in the pharmaceutical industry, coordination between researchers and factory designers is not easy. Clearly, bringing a new medicine to the market is not trivial and needs cooperation between agents which may not have the same information. According to a recent report, mistakes in the development process can increase costs by 40%.[2] Asymmetric information explains some of the complexity of research joint-venture agreements.

Uncertainty and asymmetric information are two basic ingredients of our model. We define two organizational structures. In an integrated structure, the innovation is produced in-house by the firm who then uses or markets it. This firm sets up its own research unit by financing a laboratory and hiring scientists. The contract signed between the firm and the members of the research unit is an employment contract. The manager of the firm has

[2] *"The Economist"*, November 9th, 1996, p. 77.

hierarchical authority over the research unit. Main decisions about investment, financing, development, production, and marketing of the innovation are made by the manager after possibly consulting with the research unit.

In an independent structure, the research unit is a separate firm. Financing is provided by a bank or a venture capitalist. After innovating, the firm sells the innovation to another firm by signing a joint-venture agreement or a technological alliance. The research unit installs the new process in a factory, or tests the new product for specific purposes. The user firm then operates the new technology, or produces and markets the new product.

The essential difference we introduce for these two structures is about the transferability of decision rights. In an integrated structure, decision rights cannot be credibly transfered among members of the organization. The law of contracts does not apply to such transfers. Hierarchical authority has priority over any agreement to transfer decision rights, that is, any decision to delegate decision making can be reversed by the hierarchical authority. In an independent structure, decision rights can be transfered since property rights can. We show that this essential difference is sufficient to make the choice of organizational design nontrivial.

This intuition formally translates into the following assumptions. The contract governing the relationship in an integrated structure is subject to renegotiation since decision rights cannot be credibly transferred. Such renegotiation reduces the efficiency of the organization. In an independent structure, the innovation is financed externally. Financial agency costs lead to inefficiencies which reduce the ability of the financial contract to diversify innovation risk. The two structures are afflicted by two different sources of inefficiencies: noncommitment in the integrated structure and financial market imperfections in the independent structure. The relative efficiency of the two structures depends on the characteristics of the innovation. When the cost of developing the innovation is negatively correlated with its market value, the integrated structure dominates the independent structure. The independent structure dominates in the opposite case. The basic intuition for this result goes as follows.

In the first case, the negative correlation between the development cost and market value implies that overall profits are very risky. Financial imperfections are then very costly and the integrated structure is more efficient.

We now briefly sketch how our paper relates to the literature. In the management literature, it is often argued that in-house R&D may reduce problems associated with asymmetric information, and that better coordination between innovators, production and marketing departments is achieved within an organization. With its own research unit, a firm has the scientific expertise to evaluate new technologies and new products (Armour and Teece, 1979; Lampel, Miller, and Floricel, 1996). This approach assumes that the objective of all units within the firm is to maximize the global profit of the organization. This may not be true if the units behave noncooperatively or opportunistically. A "selfish" research unit may not behave according to the organization's own interest. For example, a research unit may prefer not to reveal the true value (possibly low) of its discovery if its reward from the innovation does not provide it with such incentives. Hence, integrating the research unit within the user firm does not necessary solve the asymmetric-information problem. Incentive schemes rather than organizational form per se can mitigate the asymmetric-information problem. It may be the case, however, that different incentive schemes are possible depending on the organizational structure. This is precisely the focus of our paper.

Aghion and Tirole (1994) provide a first attempt at opening the "black box of innovation" in a incomplete-contracting framework. They suppose that R&D is a random activity performed by two risk-neutral agents, a research unit RU and the innovation user C. Its success depends on an initial investment provided by C and an noncontractible effort supplied by RU. In an integrated structure, property rights on the innovation are allocated to C. This implies that RU receives no reward for innovation. RU then supplies no effort while C supplies the optimal level of investment . In a independent structure, RU owns the innovation and bargains with C over the licensing fee once the innovation has been made. Assuming that agents have the same bargaining power, the value of innovation is equally split ex post. In this case, since each agent does not get the full return of its effort or investment, it supplies a second-best level effort or investment. The optimal structure depends on the marginal efficiency of RU's effort compared with the marginal efficiency of C's investment.

Even though our model shares some features of Aghion and Tirole's (1994) model, the basic intuition is different. They mainly stress that the innovation process is noncontractible and hence property rights are allocated as a means of alleviating contract incompleteness (as in Grossman and Hart, 1986). In a complete-contract environment, we stress that the innovation process is risky (and that this matters because RU is risk averse) and that there are informational problems reducing the efficiency of contractual agreements in sharing risk. Depending on the allocation of property rights, different contractual imperfections arise. If they are allocated to C, RU has to transfer its knowledge of the information to C and renegotiation affects the efficiency of the organization. If they are allocated to RU, renegotiation can be avoided, but financing is subject to agency costs. In this sense, the two models are complementary since they both stress important aspects of innovation activities.

Recent papers point out that bureaucratic organizations perform poorly in R&D. Dearden, Ickes and Samuelson (1990) show that a centralized structure has low incentives to adopt new technologies because of the ratchet effect. Quian and Xu (1998) argue that a soft budget constraint and an ex ante bureaucratic evaluation process can explain the centralized organizations' failure in innovating. A bureaucracy makes mistakes by rejecting promising projects and delaying innovations. In-house R&D produces high-cost innovations that are well-specified ex ante. It is, however, unable to subsidize less costly projects which may be riskier. Our model of the integrated structure has some of that flavor as noncommitment is a consequence of the nontransferability of decision rights.

The paper is organized as follows. Section 2 presents the model. Section 3 presents the main assumptions underlying both organizational structures. We analyze the integrated structure in Section 4 and the independent one in Section 5. We compare the two structures' performance in Section 6. Section 7 concludes the paper. All proofs are relegated to the Appendix.

2 The model

A research unit RU produces an innovation. When investing I in research, RU obtains a high-quality innovation h with probability $p(I)$ and a low-quality innovation l ($l < h$) with probability $1 - p(I)$. We suppose p increasing and concave, with $p(0) = 0$, $p'(0) = \infty$, $\lim_{I\to\infty} p(I) \leq 1$.

The innovation is marketed by firm C. Before selling the innovation, RU and C must operationalize its production. This is the development phase. RU incurs a development cost $D(q, \alpha)$ depending on the scale of project q and on the innovation quality α. We assume that D is increasing and convex in q, and that total and marginal development costs are decreasing in α:

$$D_q(q, \alpha) > 0,\ D_{qq}(q, \alpha) > 0,\ D(q, h) < D(q, l),\ D_q(q, h) < D_q(q, l) \quad \forall\ q > 0.$$

Following the development phase, C can start producing and marketing the product. C earns a net revenue $P(q, \alpha)$. The function P is increasing and concave in q at least on $[0, \bar{q}]$ with $\bar{q}$ large. We assume

$$P_q(q, \alpha) > 0,\ P_{qq}(q, \alpha) < 0 \quad \forall\ 0 < q < \bar{q}.$$

This function can encompass both process and product innovations. For a process innovation, the innovation quality affects the net revenue function mainly through lower production costs. For a product innovation, the innovation quality affects the net revenue function mainly through higher revenues.

For an innovation quality $\alpha \in \{l, h\}$, the R&D process generates a global profit gross of initial investment of

$$\pi(q, \alpha) = P(q, \alpha) - D(q, \alpha).$$

A high-quality innovation is assumed globally more profitable than a low-quality one, that is, $\pi(q, h) > \pi(q, l)$.

Innovations are distinguished by the relationship between revenues and development cost-s.

- Major innovation

  A type h innovation generates higher total and marginal revenues than a type l one. Formally,

  $$P(q,h) > P(q,l), \; P_q(q,h) > P_q(q,l) \quad \forall \; 0 < q < \bar{q}.$$

- Minor innovation

  A type h innovation generates lower total and marginal revenues than a type l one. Formally,

  $$P(q,h) < P(q,l), \; P_q(q,h) < P_q(q,l) \quad \forall \; 0 < q < \bar{q}.$$

For a major innovation, moving from a low-quality innovation to a high-quality innovation reduces development costs and increases revenues, that is, development costs and revenues are negatively correlated. The opposite holds for a minor innovation. It turns out that the sign of this correlation plays a significant role in our analysis.[3]

We denote by q^*_α the project size which maximizes global profit $\pi(q,\alpha)$. It is assumed that $q^*_h \geq q^*_l$, that is, a high-quality innovation is marginally more profitable than a low-quality one, regardless of whether the innovation is major or minor. We denote by I^* the investment level which maximizes the expected global profit

$$p(I)\pi(q^*_h, h) + (1 - p(I))\pi(q^*_l, l) - I.$$

RU's utility V depends on its income w net of development costs:

$$V(w,q,\alpha) = v(w - D(q,\alpha)).$$

[3]In Section 6, we give examples of both major and minor innovations.

We suppose that RU is risk averse: v is increasing and concave ($v' > 0$, $v'' < 0$). Firm C is risk neutral. Its utility U is linear in revenues net of any transfer payment w:

$$U(w, q, \alpha) = P(q, \alpha) - w.$$

Its reservation utility is normalized to zero.

We now study the organization of R&D activities under the assumption that the innovation quality is private information of RU.

3 The organization of R&D activities

We define two types of organizations. In an ***integrated structure***, R&D activities are conducted internally within firm C. RU can be seen as a division or a department of C. Firm C invests and finances the investment in research I, pays its research unit RU a wage w and develops a project of scale q.

In an ***independent structure***, RU is an autonomous firm, and it must finance its research activities externally. A competitive financier F finances the investment I and gets reimbursed R when the innovation is sold. After the research period and before the development period, RU and C negotiate a joint-venture agreement which specifies the project size q and RU's wage or royalties w. C then produces and markets the innovation.

The two structures differ in two important aspects. First, the transferability of decision rights is governed by different rules in each structure. In an integrated organization, the decision right over the project belongs to C. This right cannot be credibly transferred from C to RU as the rule of law does not govern over such intrafirm transaction. For example, even if this right was transfered to RU, C could always repossess it because it has hierarchical authority over RU. In a private-information environment, this implies that RU is communicating its information about the innovation quality to C who then uses it to decide on the project size. In an independent organization, the property right over the project initially belongs to C. Since C and RU are independent firms, this right can be "sold" from C to RU through a joint venture, and the judicial system can enforce such transaction. With the property right comes the decision right. Formally, this amounts to RU choosing the project size, using its own private information about the innovation quality.[4] The way information is communicated and used has implications for the efficiency of each structure.

Second, the financing of investment is subject to different agency costs. In an integrated structure, financing the investment is done internally. In an independent structure, RU must finance externally. We assume here, as in most of the literature in corporate finance, that external financing is subject to larger agency costs than internal financing.[5] To capture this idea, we assume that project size and payoffs are observable to C and RU, but nonobservable to F. The financial contract with F has to take this unobservability into account when specifying financial repayments.

There are three objectives to pursue when players interact. First, incentives must be provided to RU for an appropriate investment I in R&D. Second, once the innovation has been concretized, incentives must be provided to undertake an appropriate project size q. Finally, insurance must be given to RU against the risk inherent to the innovation process.

The performance of the two structures in their relative ability to pursue these objectives is compared under the assumptions that decision rights cannot be credibly transferred in an integrated structure and that external financing is costlier than internal financing. Under these assumptions, an interesting trade-off in the choice of the organization of R&D emerges.

Before solving for the optimal allocation in each structure, we characterize the symmetric-information optimal solution. It can be implemented with either structure.

- $I = I^*$, $q_\alpha = q_\alpha^*$ for $\alpha = l, h$.
- In the integrated structure, $v(w_h^{i*} - D(q_h^*, h)) = v(w_l^{i*} - D(q_l^*, l))$.

[4] Klibanoff and Poitevin (1999) explore further the issue of rights and commitment in a model of externality.

[5] See, for example, Jensen and Meckling, 1976 and Myers, 1984.

- In the independent (autonomous) structure,
  $v(w_h^{a*} - R_h^{a*} - D(q_h^*, h)) = v(w_l^{a*} - R_l^{a*} - D(q_l^*, l))$.

- $v(w_\alpha^{i*} - D(q_\alpha^*, \alpha)) = v(w_\alpha^{a*} - R_\alpha^{a*} - D(q_\alpha^*, \alpha))$ for all $\alpha \in \{l, h\}$.

First, allocative efficiency is attained for investment and project size for both qualities of innovation. For both structures, RU is fully insured against the risk of innovation. Insurance is provided by C in the integrated structure, and by F, in the independent structure. Finally, RU has the same payoff in both structures.[6]

We now assess the performance of each structure under the assumption that RU is privately informed about the quality of the innovation. Throughout, we assume that RU has the bargaining power when negotiating contracts with C and F. This assumption makes the comparison of the two structures more tractable.

4 The integrated structure

In the integrated structure, contractual negotiations and implementation are formalized by the following game.

1. RU proposes a research and development contract $c_{RD} = \{I, \{w_{\hat{\alpha}}, q_{\hat{\alpha}}\}_{\hat{\alpha}=l}^h\}$ to C who can accept it or reject it.

2. If it is accepted, RU invests I. If not, the game ends and both players obtain their reservation utility.

3. RU observes the innovation quality α, and selects a message $\hat{\alpha} \in \{l, h\}$.

   (a) RU then proposes a new contract $c_r = (w, q)$ to C.[7]

[6]Under symmetric information, both structures yield the same equilibrium allocation from the point of view of RU.

[7]Beaudry and Poitevin (1995) explain why this contract cannot contain more than one element. It would not be necessary if there were an infinite number of rounds of renegotiation.

(b) If it is rejected, the contract c_{RD} remains the outstanding contract. If c_r is accepted, it becomes the outstanding contract.

4. The innovation is developed, produced, and sold while transfers are paid as prescribed by the outstanding contract.

The fact that property rights cannot credibly be transferred from C to RU implies that RU must communicate its private information to C who then decides on the project size. Formally, this form of communication raises the possibility for C and RU to renegotiate the initial contract after RU has communicated its private information to C.[8] The possibility for renegotiation is formally taken into account in stage 3(a).

We characterize the equilibrium allocations that are not renegotiated along the equilibrium path, namely, renegotiation-proof allocations. Such allocations can be supported by equilibrium strategies that do not involve any renegotiation along the equilibrium path. A renegotiation-proof allocation $\{w_{\hat{\alpha}}, q_{\hat{\alpha}}\}_{\hat{\alpha}=l}^{h}$ must satisfy the following inequalities for all $\hat{\alpha} = l, h$.[9]

$$\begin{array}{rcllr} V(w_h, q_h, h) & \geq & \max_{(w,q)}\{V(w,q,h) \quad \text{s/t} & U(w,q,h) \geq U(w_{\hat{\alpha}}, q_{\hat{\alpha}}, h) & \\ & & & U(w,q,l) \geq U(w_{\hat{\alpha}}, q_{\hat{\alpha}}, l)\} & (RP_h^{\hat{\alpha}}) \\ V(w_l, q_l, l) & \geq & \max_{(w,q)}\{V(w,q,l) \quad \text{s/t} & U(w,q,h) \geq U(w_{\hat{\alpha}}, q_{\hat{\alpha}}), h) & \\ & & & U(w,q,l) \geq U(w_{\hat{\alpha}}, q_{\hat{\alpha}}, l)\} & (RP_l^{\hat{\alpha}}) \end{array}$$

These constraints replace the usual incentive-compatibility constraints, and therefore represent generalized incentive-compatibility constraints that incorporate the possibility of renegotiation. Each constraint $RP_{\alpha}^{\hat{\alpha}}$ implies that, given a status-quo position $(w_{\hat{\alpha}}, q_{\hat{\alpha}})$ attained following a report $\hat{\alpha}$ by RU, C only accepts those renegotiation offers that increase its utility

[8] Holmström and Myerson (1983), Maskin and Tirole (1992), and Beaudry and Poitevin (1995) all argue that this is in fact the only instance where renegotiation can have an effect. Renegotiating after the arrival of private information but before it has been communicated has no effect on the initial contract.

[9] This is shown formally in Beaudry and Poitevin (1993, 1995) when renegotiation can have an infinite or a finite number of rounds respectively.

regardless of its beliefs about the quality of the innovation. Suppose that constraint $RP_{\alpha}^{\hat{\alpha}}$ is satisfied at a status-quo position $(w_{\hat{\alpha}}, q_{\hat{\alpha}})$. For any offer that RU prefers to $(w_{\hat{\alpha}}, q_{\hat{\alpha}})$, there exists a belief for C such that it is worse off under the new offer than under the status-quo position. When assigned with this belief, C simply rejects the offer of RU. If an allocation satisfies these constraints, it is not possible for RU to increase its utility by selecting a message $\hat{\alpha}$ and then making a renegotiation offer. It is in this sense that the renegotiation-proof constraints represent generalized incentive-compatibility constraints. Since these constraints allow for renegotiation, they are more stringent than usual incentive-compatibility constraints.

We characterize the equilibrium renegotiation-proof allocation $\{I^i, \{w_\alpha^i, q_\alpha^i\}_{\alpha=l}^h\}$ that yields RU the highest expected utility.[10] It solves the following maximization problem.

$$\begin{array}{rcl} \max\limits_{\{I,\{w_\alpha,q_\alpha\}_{\alpha=l}^h\}} & & p(I)V(w_h,q_h,h)+(1-p(I))V(w_l,q_l,l) \\ \text{subject to :} & & p(I)U(w_h,q_h,h)+(1-p(I))U(w_l,q_l,l)-I=0 \qquad (IR^C) \\ V(w_h,q_h,h) & \geq & \max_{(w,q)}\{V(w,q,h) \ \text{ s/t } \ U(w,q,h)\geq U(w_{\hat{\alpha}},q_{\hat{\alpha}},h) \\ & & \qquad U(w,q,l)\geq U(w_{\hat{\alpha}},q_{\hat{\alpha}},l)\} \ \ \forall\ \hat{\alpha}=l,h \ \ (RP_h^{\hat{\alpha}}) \\ V(w_l,q_l,l) & \geq & \max_{(w,q)}\{V(w,q,l) \ \text{ s/t } \ U(w,q,h)\geq U(w_{\hat{\alpha}},q_{\hat{\alpha}},h) \\ & & \qquad U(w,q,l)\geq U(w_{\hat{\alpha}},q_{\hat{\alpha}},l)\} \ \ \forall\ \hat{\alpha}=l,h \ \ (RP_l^{\hat{\alpha}}) \end{array}$$

In this problem, RU's expected utility is maximized subject to C's participation constraint (IR^C) and the set of incentive renegotiation-proof constraints.

Proposition 1 *The equilibrium allocation $\{I^i, \{w_\alpha^i, q_\alpha^i\}_{\alpha=l}^h\}$ satisfies the following relationships.*

- *For major innovations:*

  $q_h^i = q_h^*$, $q_l^i = q_l^*$;

  $w_h^i - D(q_h^*, h) > w_l^i - D(q_l^*, l)$.

[10] There may be multiple equilibria depending on the assignment of out-of-equilibrium beliefs. We focus here on the equilibrium allocation that RU prefers. This facilitates the comparison with the independent structure.

- *For minor innovations:*

  $q_h^i = q_h^*$, $q_l^i = q_{hl}^* < q_l^*$ *where* $q_{hl}^* = \arg\max_q P(q,h) - D(q,l)$*;*

  $w_h^i - D(q_h^*, h) > w_l^i - D(q_{hl}^*, l)$.

- $p'(I^i)\{(V(w_h^i, q_h^i, h) - V(w_l^i, q_l^i, l))\,/\mathrm{E}_\alpha[v'(w_\alpha^i - D(q_\alpha^i, \alpha))|I^i] + U(w_h^i, q_h^i, h) - U(w_l^i, q_l^i, l)\} = 1$.

With symmetric information, RU's utility is equalized in both states. This implies that $w_l > w_h$ since development costs are higher in state l. Under asymmetric information, RU then has incentives to report type l when its true type is h to obtain a higher wage. The renegotiation-proof constraint RP_h^l is therefore binding, that is, when the innovation quality is high and RU announces a low-quality innovation and then renegotiates. To prevent type h from mimicking type l, the contract increases the wage gap and imposes more risk on RU. When the innovation is major, no distortion in q_l can be used ex ante to induce truth-telling because any such distortion would be renegotiated away in stage 3(a). For a minor innovation, some underproduction for the low-quality innovation is renegotiation-proof, and is therefore used to mitigate the risk allocated to RU. Finally, the normalized sum of marginal benefits to investment determines the optimal investment policy. Without specific functional forms, the investment I^i cannot be directly compared to the first-best level I^*. With risk aversion, the investment plays the dual role of determining the size of the pie and reducing the risk of the venture.

Note that by the end of the game firm C can infer the type of RU from the observation of its own profits. As in most of the literature, we implicitly assume that either ex post profits are not verifiable to third party or that it is not possible to punish RU if it had misrepresented its type. This effectively precludes C from using a forcing contract that would be based on the realization of its own profits. We now move to the analysis of the independent structure.

5 The independent structure

In an independent structure, RU seeks external financing before starting the research phase. Agents play the following game.

1. RU proposes a financial contract $c_F = \{I, \{R_{\hat{\alpha}}\}_{\hat{\alpha}=l}^{h}\}$ to F who can accept or reject it.

2. If it is accepted, RU invests I. If not, the game ends and both players obtain their reservation utility.

3. RU observes the innovation quality α. It then proposes a development contract $c_D = \{w(q)\}$ to C who can accept or reject it. If it is rejected, the financial contract is void, the game ends and all players obtain their reservation utility.

4. If it is accepted, the contract is carried out: RU implements a project size q, and a report $\hat{\alpha} \in \{l, h\}$ is sent to F; the innovation is developed, produced and sold while transfers are paid as prescribed by the contracts c_F and c_D.

The difference between this game and the one played in the integrated structure underlines the assumptions we pose for each structure. Property rights can credibly be transferred in the independent structure. The development contract allows for these rights to be transfered from C to RU through the use of a nonlinear transfer schedule. RU effectively chooses the project size q and sells it to C for royalties $w(q)$. Financing is done externally, which implies that RU and F must sign a formal contract. The project size that RU chooses is unobservable to F, and hence the financial payment R from RU to F must depend on a report that RU sends to F.

In Lemma 1, we characterize the optimal financial contract.

Lemma 1 *Without loss of generality, the equilibrium financial contract* $\{I^a, \{R^a_{\hat{\alpha}}\}_{\hat{\alpha}=l}^{h}\}$ *is such that* $R^a_l = R^a_h = I^a$.

Because F cannot observe output nor revenue, the optimal financial contract is a debt contract where the financial repayment is independent of the quality of the innovation.[11] Furthermore, this payment is equal to the lent amount, I^a, so that F breaks even. Given this result, the separating-equilibrium allocation of the independent structure, $\left\{I^a, \{w^a(q_\alpha), q_\alpha^a\}_{\alpha=l}^h\right\}$, that maximizes the expected utility of RU is the solution to the following maximization problem.[12]

$$\begin{aligned}
\max_{\left\{I,\{w(q_\alpha),q_\alpha\}_{\alpha=l}^h\right\}} \quad & p(I)V(w(q_h)-I,q_h,h)) + (1-p(I))V(w(q_l)-I,q_l,l) & \\
\text{subject to}: \quad & U(w(q_h),q_h,h) \geq 0 & (IR_h^C)\\
& U(w(q_l),q_l,l) \geq 0 & (IR_l^C)\\
& V(w(q_h)-I,q_h,h) \geq V(w(q_l)-I,q_l,h) & (IC_h)\\
& V(w(q_l)-I,q_l,l) \geq V(w(q_h)-I,q_h,l) & (IC_l)
\end{aligned}$$

RU's expected utility is maximized subject to C's participation constraints (IR_α^C) and RU's incentive-compatibility constraints (IC_α).

Proposition 2 *The equilibrium allocation satisfies the following relationships.*

- $P(q_\alpha^a,\alpha) - w^a(q_\alpha^a) = 0 \;\; \forall\; \alpha \in \{l,h\}$.
- *For major innovations:*
  $q_l^a = q_l^*,\; q_h^a = \begin{cases} q_h^* & if\;\; \pi(q_l^*,l) \geq P(q_h^*,h) - D(q_h^*,l) \\ q_h^S & otherwise \end{cases}$
  with $q_h^S > q_h^*$ *such that* $\pi(q_l^*,l) = P(q_h^S,h) - D(q_h^S,l)$*;*
  $w_h^a - D(q_h^a,h) > w_l^a - D(q_l^*,l)$.
- *For minor innovations:*
  $q_h^a = q_h^*,\; q_l^a = \begin{cases} q_l^* & if\;\; \pi(q_h^*,h) \geq P(q_l^*,l) - D(q_l^*,h) \\ q_l^S & otherwise \end{cases}$

[11] We implicitly assume that the debt contract is riskless. Incorporating the possibility of default would not alter our main conclusions provided that F could audit RU at a cost (Townsend, 1979).

[12] This is the only equilibrium allocation that survives the application of the Intuitive criterion of Cho and Kreps (1987).

with $q_l^S < q_l^*$ *such that* $\pi(q_h^*, h) = P(q_l^S, l) - D(q_l^S, h)$;
$w_h^a - D(q_h^*, h) > w_l^a - D(q_l^a, l)$.

- $p'(I^a)\left\{\left(V(w_h^a, q_h^a, h) - V(w_l^a, q_l^a, l)\right)/\mathrm{E}_\alpha[v'(w_\alpha^a - D(q_\alpha^a, \alpha))|I^a]\right\} = 1.$

The main consequence of imperfect external financing is that F cannot provide any insurance to RU since financial repayments are the same in each state of nature. C cannot provide insurance either since its contract is negotiated once the innovation has been realized. RU supports all research risk. Investment is therefore determined by the incremental value for RU of a high-quality innovation compared to a low-quality one. The development contract is negotiated in a signaling environment where prior beliefs $p(I)$ do not affect the separating allocation. Since the financial contract influences only beliefs (through the choice of investment), the specifics of the development contract do not depend on the financial contract. In the development contract, C's individual-rationality constraints are binding. For a major innovation, C's revenues are higher for a high-quality innovation. RU can therefore extract more royalties from C. RU then wants to overstate the quality of the innovation, and the binding incentive constraint is that for a low-quality innovation. If it is binding, RU overproduces in state h to satisfy the incentive constraint of type l. The exact opposite holds for a minor innovation. RU underproduces in state l to satisfy the incentive constraint of type h.

The nonlinear transfer schedule is such that RU's incentives to behave truthfully are preserved. For all nonequilibrium output levels, the transfer is set at a large negative number. The equilibrium wage is such that RU earns more when the innovation is type h than when it is type l. Finally, the marginal benefit to investment accruing to RU normalized by its expected marginal utility determines the optimal investment policy. Again, without specific functional forms, the investment I^i cannot be directly compared to the first-best level I^*. With risk aversion, the investment plays the dual role of determining the size of the pie and reducing the risk of the venture.

In the next section, we compare the performance of the two structures.

6 Performance of the two structures

The criterion to identify the optimal structure is RU's expected utility. Since all other players earn zero expected profits and utility is transferable through contractual payments, this is the appropriate selecting criterion. We first establish a benchmark case in the following lemma.

Lemma 2 *Suppose that $P(q,l) = P(q,h)$. Both organizational structures yield the same expected payoff to RU.*

This lemma establishes that when C's payoff does not depend on the quality of innovation, both structures perform equivalently from the point of view of RU. In the integrated structure, renegotiation-proof constraints impose ex post efficiency in production and no risk sharing. When C's payoff is independent of innovation quality, the threat of renegotiation eliminates all possibility for sharing risk since C accepts all renegotiation offers that do not decrease its expected payoff regardless of the innovation quality. When C's payoff is independent of the innovation quality, this implies that C must earn the same payoff for each type of innovation. Hence, no risk sharing is possible.

In the independent structure, the financial contract provides no risk sharing, while the contract with C yields ex post efficiency in production and no risk sharing. Ex post efficiency is attained since C's payoff does not depend on the innovation quality. Contractual negotiations between RU and C are therefore frictionless.

Both organizational structures yield efficient production and provide no risk sharing to RU. The level of investment is therefore the same under both structures. Consequently, both structures perform equivalently when C's payoff is independent of the innovation quality.

We now assume that the innovation quality affects C's payoff. The comparison of the two organizational structures depends on whether the innovation is major or minor. We analyze these two cases in turn.

• Major innovation

Recall that for a major innovation, a type h innovation generates higher total and marginal revenues than a type l one. Formally,

$$P(q,h) > P(q,l), \;\; P_q(q,h) > P_q(q,l) \quad \forall\; 0 < q < \bar{q}.$$

We can establish the superiority of the integrated structure when the innovation is major.

Proposition 3 *For major innovations, the integrated structure yields a higher expected payoff to RU than the independent structure.*

The intuition for this result can be given in terms of the effects of contractual imperfections on the extent of risk sharing provided to RU. Agency costs come from the fact that contracts insure RU against the risk of innovation, and risk sharing conflicts with asymmetric information. When C's payoff is independent of the quality of innovation, both structures are equivalent. Now suppose that a low-quality innovation generates slightly lower marginal and total revenues than a high-quality one. In the independent structure, this worsens risk sharing as the difference between the total value of a high and a low innovation increases. It increases since the profitability of the low-quality innovation decreases. Since RU gets the residual value in each state and there is debt financing, RU supports the full loss from such decrease, thus bearing more risk and reducing its expected payoff. In the integrated structure, RU supports the full loss from the reduction in the profitability of the low-quality innovation. Risk-sharing is, however, unaffected as all increase in risk is supported by C. The integrated structure then dominates the independent structure since the former provides better insurance to RU than the latter.

• Minor innovation

Recall that for a minor innovation, a type h innovation generates lower total and marginal revenues than a type l one. Formally,

$$P(q,h) < P(q,l), \;\; P_q(q,h) < P_q(q,l) \quad \forall\; 0 < q < \bar{q}.$$

We can establish the superiority of the independent structure when the innovation is minor (under some other condition).

Proposition 4 *Suppose that* $\pi(q_l^S, l) \geq \pi(q_{hl}^*, l)$ *where* $\pi(q_h^*, h) = P(q_l^S, l) - D(q_l^S, h)$ *and* $q_{hl}^* = \arg\max_q P(q,h) - D(q,l)$*. For minor innovations, the independent structure yields a higher expected payoff to RU than the integrated structure.*

Suppose that a low-quality innovation generates slightly higher marginal revenues than a high-quality one. In the independent structure, this improves risk sharing as the difference between the total value of a high and a low innovation shrinks. This difference shrinks since the profitability of the low-quality innovation increases. Since C gets its reservation value in each state and financing is achieved through debt, RU gets all benefits from such increase, thus increasing its expected payoff and improving risk sharing. In the integrated structure, the renegotiation-proof constraint becomes less stringent and therefore allows for some distortion in q_l to improve risk sharing. Such distortion implies that RU cannot appropriate the whole surplus generated by the increase in revenues. The independent structure then dominates the integrated structure.

The assumption that $\pi(q_l^S, l) \geq \pi(q_{hl}^*, l)$ is satisfied for innovations that do not generate extreme differences in revenues, that is, when $P(q,l)$ is not too different from $P(q,h)$. This is a sufficient condition for the result to obtain. It is, however, not necessary. The precise characterization of a necessary and sufficient condition is not easy to obtain and we limit our analysis to this assumption.

The difference between the two cases stems from the effect of technology on the amount of risk in the venture. From a situation where there is no revenue risk, increasing revenues for low-quality innovations reduces the total risk in $P(q,\alpha) - D(q,\alpha)$. In the independent structure, RU supports all risk. It therefore gains from the increase in revenue as well as from the reduction in risk. The independent structure is then optimal. When the revenues of low-quality innovations is decreased, the opposite holds. Total risk is increased. In the independent structure, RU supports all this extra risk while also losing from the loss in revenue. The integrated structure is then optimal.

This result has a testable implication. We show that major innovations are produced in-house, while minor ones tend to be produced in independent firms. Consider the case of the pharmaceutical industry described in the Introduction. Development activities consist in testing the new drug. The development process starts with toxicology analyzes and goes through clinical trials on animals, on human volunteers and finally on patients (small samples and then large samples). The new drug must be patented before entering the trial process. The patent-protection lasts twenty years, while the trial process can take several years.[13] Saving time during the development phase is therefore particularly important. Every day saved on trial is an extra day of patent protection saved. The trial period of an innovation is long and costly, and it lowers its patent protection, hence the gross profit of the marketing firm. There is a negative correlation between development costs and revenues. This corresponds to the case of a major innovation. Our model then predicts that R&D activities are more efficiently organized in-house. Although there is some research done externally in the pharmaceutical industry, casual evidence seems to suggest that a lot of it is undertaken in large pharmaceutical firms. Asymmetric information and contractual imperfections can explain this organizational form. It reinforces the effect of other factors such as economies of scale in research, large financing requirements, etc.

For a technological innovation, it is often the case that when the cost to develop and install a new technology is high, savings on production costs are also high. Consider the information-technology industry. Suppose that a firm can reduce its costs by using a more efficient communication network. A new network is costly to install but can treat a lot of information very quickly. Only improving the existing network is relatively cheap to install, but it is usually less efficient. The software industry is another example. When a new version of an existing software or system is adopted by a firm, the costs incurred by the research unit (mostly the training of the user firm's employers) are low and savings are also low. When

[13] *The Economist,* February 21st, 1998, Survey of the Pharmaceutical Industry, pp. 3-5; Tapon and Cadsby (1996).

the new software or system is very different, and therefore needs more training, savings on production costs can be very high. In these two examples, there is a positive correlation between development and installation costs and revenues. This corresponds to the case of a minor innovation. Our model then predicts that such innovations tend to be produced by independent firms. Again, there is casual evidence for this. Many firms outsource the management of information technology. Consequently, a lot of firm-specific software is being developed by independent sub-contractors.

Our explanation of these facts rests on asymmetric information and contractual imperfections. Integrated firms tend to be inefficient because it is easy to deviate from an initial plan, which we model here as renegotiation. Independent firms incur agency costs when seeking external financing, which we model here as nonobservability of profits by the financier. We believe that a different formulation for these agency costs would still yield a tradeoff between the two structures that is qualitatively similar to the one characterized here. The advantage of our modeling assumptions is that it yields results which seem to broadly fit some stylized facts.

Our model makes sharp predictions about the organization of R&D. In reality, firms may pursue some R&D activities in-house as well as buy some innovations from independent firms. This can easily be reconciled with our results. Minor innovations would mostly be acquired on the market while major innovations would tend to be produced in-house. Alternatively, suppose that firms do not know in advance whether the innovation will be major or minor. Firms may diversify this risk by supporting both in-house and external R&D activities. The intensity of each type of organization would then depend on the likelihood of each type of innovation quality.

We can give a final interpretation to our results. Suppose that integrated firms tend to be larger firms, while independent firms are mostly small R&D firms. Our model predicts that it is efficient for large firms to develop drastic innovation (those for which the variance is high), while small firms strive for the less drastic ones.

7 Conclusion

This paper studies the optimal structure of R&D activities in a model with a random research process, asymmetric information about its outcome and heterogeneity in players' attitude toward risk. When contracts can be renegotiated and profits are nonobservable to external financiers, a tradeoff emerges for the optimal organization of research activities. In a previous version of this paper, we show that these are necessary assumptions for this tradeoff to emerge. When agents can commit and profits are observable to external financiers (but RU still has some private information), both structures are equivalent. External financiers can provide the same risk sharing as C does in the integrated structure. Asymmetric information is not sufficient per se to explain the organization of research activities. More contractual imperfections are needed for a tradeoff between the two structures to emerge.

An interesting extension would be to study the strategic role of organizational structure in imperfect output markets. Our model can provide a crude and partial analysis. For major innovations, expected output is higher under the independent structure than under the integrated structure. With imperfect output markets and Cournot competition, an independent organization of research activities yields a competitive advantage by committing to a larger output. This advantage would have to be weighted against the optimality of the integrated structure when there is no strategic consideration.

For minor innovations, expected output is higher under the independent structure under the assumption of Proposition 4, so that the presence of imperfect output markets would reinforce the case for the optimality of the independent structure. When $\pi(q_l^S, l) < \pi(q_{hl}^*, l)$, however, expected output is larger under the integrated structure, and again a tradeoff would emerge. A full analysis of these considerations is certainly worthwhile.

A Proof of Proposition 1

We characterize the solution to a relaxed maximization problem in which only constraints (IR^C) and (RP^l_h) are included. We then show that, at this solution the omitted constraints are satisfied. The proof treats alternatively the cases of major and minor innovations.

Major innovation

Since the only incentive constraint is (RP^l_h), it follows that $q^i_h = q^*_h$. The constraint (RP^l_h) is strictly binding which implies that the allocation $\{w^i_l, q^i_l\}$ is on the curve $U(w,q,l)$ that is tangent to $V(w^i_h, q^*_h, h)$, that is, by mimicking type l, the best renegotiation offer that type h can make and that C is sure to accept is along this curve $U(w,q,l)$. Furthermore, doing so would give type h exactly its equilibrium payoff. The equilibrium contract of type l is therefore on the curve $U(w,q,l)$ that is tangent to $V(w^i_h, q^*_h, h)$. This fixes the payoff that C gets from its contract with type l. Given this, type l's allocation must be its preferred contract on this curve. It is easy to show that this implies that $q^i_l = q^*_l$. Project size has now been determined for each type. Wages are adjusted such that (IR^C) and (RP^l_h) are strictly binding. Since project sizes are efficient, the constraints (RP^α_α) for $\alpha = l, h$ are satisfied. And, it is easy to show that, if (RP^l_h) is strictly binding, then (RP^h_l) is satisfied. Finally, since both utility curves (for the two types) are tangent to the same $U(w,q,l)$ curve and since type h has lower development costs, we have $w^i_h - D(q^*_h, h) > w^i_l - D(q^*_l, l)$.

Minor innovation

Since the only incentive constraint is (RP^l_h), it follows that $q^i_h = q^*_h$. The constraint (RP^l_h) is strictly binding which implies that the allocation $\{w^i_l, q^i_l\}$ is on the curve $U(w,q,h)$ that is tangent to $V(w^i_h, q^*_h, h)$, that is, by mimicking type l, the best renegotiation offer that type h can make and that C is sure to accept is along this curve $U(w,q,h)$.[14] Furthermore, doing so would give type h exactly its equilibrium payoff. The equilibrium contract of type l is therefore on the curve $U(w,q,h)$ that is tangent to $V(w^i_h, q^*_h, h)$. Given this, type l's allocation must be its preferred contract on this curve from the point of view of type l. It is easy to show that this implies that $q^i_l = q^*_{hl} < q^*_l$ since a type h innovation generates less revenue than a type l. Project size has now been determined for each type. Wages are adjusted such that (IR^C) and (RP^l_h) are strictly binding. Since $q^i_h = q^*_h$, the constraint (RP^h_h)

[14] The assumption about the relative profitability of the high-quality innovation with respect to the low-quality innovation explains the difference in the set of renegotiation offers that C is sure to accept for the cases of major and minor innovations.

is satisfied. Since q^*_{hl} is such that $V(w,q,l)$ is tangent to $U(w,q,h)$, the constraint (RP^l_l) is satisfied. And, it is easy to show that, if (RP^l_h) is strictly binding, then (RP^h_l) is satisfied. Finally, since both utility curves (for the two types) are tangent to the same $U(w,q,h)$ curve and since type h has lower development costs, we have $w^i_h - D(q^*_h, h) > w^i_l - D(q^*_{hl}, l)$.

Investment

We now determine investment. Define $\Delta f = f(w^i_h, q^i_h, h) - f(w^i_l, q^i_l, l)$ for $f = U, V$. C's marginal benefit from a high-quality innovation is

$$\Delta U = P(q^*_h, h) - w^i_h - \left(P(q^i_l, l) - w^i_l\right).$$

The binding renegotiation-proof constraint (RP^l_h) yields $w^i_h - w^i_l = P(q^*_h, h) - P(q^i_l, h)$. Therefore, $\Delta U = P(q^i_l, h) - P(q^i_l, l)$. Substituting for this in the constraint (IR^C) and computing the first-order condition with respect to investment yields:

$$p'(I^i)\Delta V + \lambda\left(p'(I^i)\Delta U - 1\right) = 0,$$

where λ is the Lagrange multiplier on constraint (IR^C). It is easy to show (from the other first-order conditions) that $\lambda = \mathrm{E}_\alpha[v'(w^i_\alpha - D(q^i_\alpha, \alpha))|I^i]$. The first-order condition can be rewritten as:

$$p'(I^i)\left\{\left(V(w^i_h, q^i_h, h) - V(w^i_l, q^i_l, l)\right)/\mathrm{E}_\alpha[v'(w^i_\alpha - D(q^i_\alpha, \alpha))|I^i] + U(w^i_h, q^i_h, h) - U(w^i_l, q^i_l, l)\right\} = 1.$$

Finally, we give an informal description of strategies and beliefs that support this allocation as a PBE of the game. We start with the last stage. In stage 3a and 3b, RU offers its preferred contract within the set of contracts that C accepts, that is, contracts which increase C's payoff regardless of its beliefs. C rejects all other contracts on the belief that it was offered by the type on which C would lose if it was accepted. In stage 3, RU selects the message which yields the highest payoff taking into account the possibilities for a successful renegotiation. In the first stage, RU proposes the contract characterized above. C accepts all contracts that yield zero expected profit taking into account the reporting strategy and its own acceptance decision at the renegotiation stage. Along the path, RU proposes the characterized contract which C accepts. RU truthfully reveals its type when reporting, and makes no renegotiation offer. *Q.E.D.*

B Proof of Lemma 1

Suppose that $R^a(l) \neq R^a(h)$. In stage 4, RU would report $\hat{\alpha} = \arg\min_\alpha R^a(\alpha)$. Without loss of generality, F would therefore accept a contract such that $R^a(l) = R^a(h)$. To break even, it must be that $R^a(l) = R^a(h) = I^a$. *Q.E.D.*

C Proof of Proposition 2

The subgame starting in stage 3 is a signaling game played between RU and C and is parameterized by the investment I which is observable to all players. We characterize the separating equilibrium that maximizes RU's expected utility. This equilibrium is also the one that would survive the application of the Intuitive criterion (Cho and Kreps, 1987). In this equilibrium, C earns zero profit on each type, which implies that $w^a(q^a_\alpha) = P(q^a_\alpha, \alpha)$ for all α.

Major innovation

Since $P(q, h) > P(q, l)$ for all $q > 0$, it is type l that may have incentive in mimicking type h to obtain a higher wage. This implies that there is no distortion in type l's project size, that is, $q^a_l = q^*_l$. After substituting for the equilibrium wages, constraint (IC_l) reduces to

$$v(P(q^*_l, l) - I^a - D(q^*_l, l)) \geq v(P(q^a_h, h) - I^a - D(q^a_h, l)),$$

which is equivalent to

$$\pi(q^*_l, l) \geq P(q^a_h, h) - D(q^a_h, l).$$

If this is satisfied at $q^a_h = q^*_h$, then this is the solution. If not, $q^a_h = q^S_h$ where q^S_h is the maximal solution to

$$\pi(q^*_l, l) = P(q^a_h, h) - D(q^a_h, l).$$

Finally, $w^a_h - D(q^a_h, h) > w^a_l - D(q^*_l, l)$ since constraint IC_l is satisfied and type h has lower development costs than type l.

Minor innovation

Since $P(q,h) < P(q,l)$ for all $q > 0$, it is type h that may have incentive in mimicking type l to obtain a higher wage. This implies that there is no distortion in type h's project size, that is, $q_h^a = q_h^*$. After substituting for the equilibrium wages, constraint (IC_h) reduces to

$$v(P(q_h^*, h) - I^a - D(q_h^*, h)) \geq v(P(q_l^a, l) - I^a - D(q_l^a, h)),$$

which is equivalent to

$$\pi(q_h^*, h) \geq P(q_l^a, l) - D(q_l^a, h).$$

If this is satisfied at $q_l^a = q_l^*$, then this is the solution. If not, $q_l^a = q_l^S$ where q_l^S is the minimal solution to

$$\pi(q_h^*, h) = P(q_l^a, l) - D(q_l^a, h).$$

Finally, $w_h^a - D(q_h^*, h) > w_l^a - D(q_l^a, l)$ since constraint IC_h is satisfied and type l has higher development costs than type h.

Investment

Investment is determined using first-order conditions in a similar fashion as in the proof of Proposition 1. These steps are not reproduced here.

Finally, we give an informal description of strategies and beliefs that support this allocation as a PBE of the game. We start with the last stage. In the fourth stage, RU reports to F the type that minimizes its financial repayment, and implements its preferred project size. In stage 3, RU proposes the contract characterized above, and C accepts all contracts that yield zero expected profits on each type. All other contracts are rejected on the belief that they were offered by type l when the innovation is major and type h when the innovation is minor. In stage 1, RU offers the financial contract characterized above and in Lemma 1. All contracts yielding negative expected profits are rejected by F. These contracts are evaluated taking into account that RU always pays the lowest repayment specified in the contract. *Q.E.D.*

D Proof of Lemma 2

First, define $\Delta f^x = f(w_h^x, q_h^x, h) - f(w_l^x, q_l^x, l)$ for $f = U, V$ and $x = i, a$. Consider the optimal allocation under the integrated structure. Using Proposition 1, the output vector is $q_\alpha^i = q_\alpha^*$ for $\alpha = l, h$. Since $U(w, q, l) = U(w, q, h)$, We know from the proof of Proposition 1 that both allocations must be on the same curve $U(w, q, l)$ (or $U(w, q, h)$). This implies that $P(q_l^*, l) - w_l^i - I^i = P(q_h^*, h) - w_h^i - I^i = 0$, where the last equality comes from the binding participation constraint. Hence, $w_\alpha^i = P(q_\alpha^*, \alpha) - I^i$. RU then earns in state α: $v\left(P(q_\alpha^*, \alpha) - I^i - D(q_\alpha^*, \alpha)\right)$. Finally, the investment is determined by

$$p'(I^i)\left\{\Delta V^i / \mathrm{E}_\alpha\left[v'\left(P(q_\alpha^*, \alpha) - I^i - D(q_\alpha^*, \alpha)\right)|I^i\right]\right\} = 1.$$

In the independent structure, we can use Proposition 2 to show that the output vector is $q_\alpha^i = q_\alpha^*$ for $\alpha = l, h$. We also know from C's participation constraints that $P(q_l^*, l) - w^a(q_l^*) = P(q_h^*, h) - w^a(q_h^*) = 0$. Hence, $w^a(q_\alpha^*) = P(q_\alpha^*, \alpha)$. The financial payment given in Lemma 1 is $R^a(\alpha) = I^a$. RU then earns in state α: $v\left(P(q_\alpha^*, \alpha) - I^a - D(q_\alpha^*, \alpha)\right)$. Finally, the investment is determined by

$$p'(I^a)\left\{\Delta V^a / \mathrm{E}_\alpha\left[v'\left(P(q_\alpha^*, \alpha) - I^a - D(q_\alpha^*, \alpha)\right)|I^a\right]\right\} = 1.$$

For both structures, RU earns the same expected payoff and the same investment is undertaken. Both structures are therefore equivalent. *Q.E.D.*

E Proof of Proposition 3

In the integrated structure, the optimal allocation solves the following maximization problem

$$\begin{aligned}
&\max_{\left\{I, \{w_\alpha, q_\alpha\}_{\alpha=l}^h\right\}} && p(I)V(w_h, q_h, h) + (1 - p(I))V(w_l, q_l, l) && \\
&\text{subject to}: && p(I)U(w_h - I, q_h, h) + (1 - p(I))U(w_l - I, q_l, l) \geq 0 && (IR^C) \\
& && V(w_h, q_h, h) \geq \max_{(w,q)}\{V(w, q, h) \;\; \text{s/t} \;\; U(w, q, l) \geq U(w_l, q_l, l)\} && (RP_h^l)
\end{aligned}$$

where all nonbinding constraints have been removed, and the participation constraint has been rewritten by inserting I inside the function U, which is possible because U is linear in income.

In the independent structure, the optimal allocation solves the following maximization problem

$$
\begin{array}{rll}
\max\limits_{\left\{I,\{w(q_\alpha),q_\alpha\}_{\alpha=l}^{h}\right\}} & p(I)V(w(q_h)-I,q_h,h)+(1-p(I))V(w(q_l)-I,q_l,l) & \\
\text{subject to}: & U(w(q_h),q_h,h)\geq 0 & (IR_h^C) \\
& U(w(q_l),q_l,l)\geq 0 & (IR_l^C) \\
& V(w(q_l)-I,q_l,l)\geq V(w(q_h)-I,q_h,l) & (IC_l)
\end{array}
$$

where the nonbinding incentive constraint has been removed. This problem can be transformed using the following change in variables. Define $w_\alpha \equiv w(q_\alpha)-I$. The maximization problem then becomes

$$
\begin{array}{rll}
\max\limits_{\left\{I,\{w_\alpha,q_\alpha\}_{\alpha=l}^{h}\right\}} & p(I)V(w_h,q_h,h)+(1-p(I))V(w_l,q_l,l) & \\
\text{subject to}: & U(w_h-I,q_h,h)\geq 0 & (IR_h^C) \\
& U(w_l-I,q_l,l)\geq 0 & (IR_l^C) \\
& V(w_l,q_l,l)\geq V(w_h,q_h,l) & (IC_l)
\end{array}
$$

Suppose first that the constraint (IC_l) is not binding in the above problem. The solution then entails $q_\alpha^a=q_\alpha^*$. This solution satisfies all constraints in the relaxed problem for the integrated structure, that is, constraints (IR^C) and (RP_h^l). Since both maximization problems have the same objective function, it has to be the case that the integrated-structure solution yields a higher payoff than the independent-structure one. Now, suppose that constraint (IC_l) is binding. The payoff for the independent structure is decreased, while that of the integrated structure is left unchanged. The integrated structure then yields a higher payoff in this case as well. *Q.E.D.*

F Proof of Proposition 4

In the integrated structure, the optimal allocation solves the following maximization problem

$$
\begin{array}{rll}
\max\limits_{\left\{I,\{w_\alpha,q_\alpha\}_{\alpha=l}^{h}\right\}} & p(I)V(w_h,q_h,h)+(1-p(I))V(w_l,q_l,l) & \\
\text{subject to}: & p(I)U(w_h-I,q_h,h)+(1-p(I))U(w_l-I,q_l,l)\geq 0 & (IR^C) \\
& V(w_h,q_h,h)\geq \max_{(w,q)}\{V(w,q,h)\ \text{ s/t }\ U(w,q,l)\geq U(w_l,q_l,l)\} & (RP_h^l)
\end{array}
$$

where all nonbinding constraints have been removed, and the participation constraint has been rewritten by inserting I inside the function U, which is possible because U is linear in income. For minor innovations, we know from Proposition 1 that $q_h^i = q_h^*$ and $q_l^i = q_{hl}^*$. The constraint (RP_h^l) is binding, and therefore we have

$$w_l^i = P(q_{hl}^*, h) - P(q_h^*, h) + w_h^i.$$

Substituting for this in the constraint (IR^C) and solving for w_h yields

$$w_h^i = P(q_h^*, h) - I + (1 - p(I)) \left(P(q_{hl}^*, l) - P(q_{hl}^*, h) \right).$$

The maximization problem then becomes

$$\max_I \; p(I)V(w_h^i, q_h^*, h) + (1 - p(I))V(w_l^i, q_{hl}^*, l).$$

Expanding yields

$$\begin{aligned} \max_I \quad & p(I)v \left(P(q_h^*, h) - I + (1 - p(I)) \left(P(q_{hl}^*, l) - P(q_{hl}^*, h) \right) - D(q_h^*, h) \right) + \\ & (1 - p(I))v \left(P(q_{hl}^*, h) + (1 - p(I)) \left(P(q_{hl}^*, l) - P(q_{hl}^*, h) \right) - I - D(q_{hl}^*, l) \right). \end{aligned}$$

This can be simplified to

$$\begin{aligned} \max_I \quad & p(I)v \left(\pi(q_h^*, h) + (1 - p(I)) \left(P(q_{hl}^*, l) - P(q_{hl}^*, h) \right) - I \right) + \\ & (1 - p(I))v \left(\pi(q_{hl}^*, l) - p(I) \left(P(q_{hl}^*, l) - P(q_{hl}^*, h) \right) - I \right). \end{aligned}$$

In the independent structure, the optimal allocation solves the following maximization problem

$$\begin{aligned} \max_{\left\{I, \{w(q_\alpha), q_\alpha\}_{\alpha=l}^h\right\}} \quad & p(I)V(w(q_h) - I, q_h, h)) + (1 - p(I))V(w(q_l) - I, q_l, l) & \\ \text{subject to:} \quad & U(w(q_h), q_h, h) \geq 0 & (IR_h^C) \\ & U(w(q_l), q_l, l) \geq 0 & (IR_l^C) \\ & V(w(q_h) - I, q_h, h) \geq V(w(q_l) - I, q_l, h) & (IC_h) \end{aligned}$$

where the nonbinding incentive constraint has been removed. For minor innovations, we know from Proposition 2 that $q_h^a = q_h^*$ and $q_l^a = q_l^S$. Both participation constraints are binding which implies that $w^a(q_\alpha^a) = P(q_\alpha^a, \alpha)$. Substituting for them in the objective function yields

$$\max_I \; p(I)v \left(P(q_h^*, h) - I - D(q_h^*, h) \right) + (1 - p(I))v \left(P(q_l^S, l) - I - D(q_l^S, l) \right),$$

which simplifies to

$$\max_I p(I)v\left(\pi(q_h^*,h)-I\right)+(1-p(I))v\left(\pi(q_l^S,l)-I\right).$$

Define

$$\begin{aligned}
\underline{x} &= \pi(q_h^*,h)-I\\
\bar{x} &= \pi(q_h^*,h)+(1-p(I))\left(P(q_{hl}^*,l)-P(q_{hl}^*,h)\right)-I\\
\underline{y} &= \pi(q_{hl}^*,l)-p(I)\left(P(q_{hl}^*,l)-P(q_{hl}^*,h)\right)-I\\
\bar{y} &= \pi(q_l^S,l)-I.
\end{aligned}$$

Under the assumption of the proposition, we have $\underline{x}<\bar{x}$ and $\underline{y}<\bar{y}$. Since v is strictly concave and increasing, we have for all $\underline{z}<\bar{z}$,

$$v(\bar{z})-v(\underline{z})<v'(\underline{z})(\bar{z}-\underline{z}) \quad\text{and}\quad v(\bar{z})-v(\underline{z})>v'(\bar{z})(\bar{z}-\underline{z}).$$

Hence,

$$\begin{aligned}
p(I)(v(\bar{x})-v(\underline{x})) &< p(I)v'(\underline{x})(\bar{x}-\underline{x})\\
(1-p(I))(v(\bar{y})-v(\underline{y})) &> (1-p(I))v'(\bar{y})(\bar{y}-\underline{y}).
\end{aligned}$$

This implies that

$$(1-p(I))(v(\bar{y})-v(\underline{y}))+p(I)v'(\underline{x})(\bar{x}-\underline{x})>p(I)(v(\bar{x})-v(\underline{x}))+(1-p(I))v'(\bar{y})(\bar{y}-\underline{y}).$$

Rearranging terms yields

$$\begin{aligned}
&\{p(I)v(\underline{x})+(1-p(I))v(\bar{y})\}>\\
&\quad\left\{p(I)v(\bar{x})+(1-p(I))v(\underline{y})\right\}+(1-p(I))v'(\bar{y})(\bar{y}-\underline{y})-p(I)v'(\underline{x})(\bar{x}-\underline{x}).
\end{aligned}$$

The left-hand-side term is the objective function for the independent structure. The first term of the right-hand side is the objective function for the integrated structure. The second term simplifies to

$$(1-p(I))\left\{p(I)\left(v'(\bar{y})-v'(\underline{x})\right)\left(P(q_{hl}^*,l)-P(q_{hl}^*,h)\right)+v'(\bar{y})\left(\pi(q_l^S,l)-\pi(q_{hl}^*,l)\right)\right\}>0.$$

We know that $\bar{y}<\underline{x}$. Concavity of v implies that $v'(\bar{y})>v'(\underline{x})$. For minor innovations, $P(q_{hl}^*,l)>P(q_{hl}^*,h)$. This establishes that the first term in the expression is positive. Under the assumption of the proposition, the second term is positive. The whole expression is therefore positive.

This implies that the objective function of the independent structure is larger than the objective function of the integrated structure for all I. The independent structure then yields a higher payoff to RU than does the integrated structure. *Q.E.D.*

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