The ownership and financing of innovation in R&D races

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The ownership and financing of innovation in R&D races

Abstract

This paper develops a theory of the organization and financing of innovation activities where integration, venture capital financing, and strategic alliances emerge as optimal responses to competitive pressures of the R&D race, research intensity of R&D projects, the stage of the research and product development, and the severity of the financial constraints. We model the relationship between a research unit and its downstream firm in the context of a R&D race with a competing pair. We show that the choice of organization and financial structure of R&D plays a strategic role by committing a research unit and its downstream firm to an accelerated R&D activity. We find that integrated organization structures are more likely to emerge when R&D projects have low research intensity, competition in the R&D race is more intense or the R&D cycle involves late-stage research, and when the research unit is financially constrained. Non-integration and independent venture capital financing are more likely to emerge when R&D projects have high research intensity, when competition in the R&D race is less intense or the R&D cycle involves early-stage research, and when the research unit is not financially constrained. Finally, corporate venture capital and strategic alliances are more likely to emerge when competition in the R&D race is more intense, the R&D cycle involves late-stage research, and when projects have high research intensity.

1. Introduction

The importance of Research & Development (R&D) in mature economies has increased dramatically in the recent years. In globally competitive environments, innovation plays a crucial role in the value creation process, and R&D management has become a strategic tool for companies to gain competitive advantage in a "knowledge based" economy. This raises fundamental questions: What is the optimal ownership and financial structure of innovation? Should innovation be performed within a firm, or should it be outsourced to specialized research units external to the firm? Should basic research be financed by outside private equity (i.e. independent venture capitalists) or through strategic alliances and corporate venture capital ? What is the effect of competitive pressures in R&D races on the ownership and financing of innovation?

For their R&D activities, firms choose a variety of organizational and financial arrangements. For instance, Nokia, the telecommunications giant, undertakes basic research mainly in-house or in one of its research sub-division.[1] In the computer industry, for its Apple II model, Apple Computer outsourced 70% of its manufacturing costs and components, including critical components (such as design) to benefit from its vendors' R&D and technical expertise.[2] In the pharmaceutical industry, Merck, the drug firm, invests 95% of its research spending in in-house R&D and only 5% in external research laboratories (Ambec and Poitevin, 2000). Another big player in the same industry, Novartis, has recently entered into an $800 million "research alliance" with Vertex Pharmaceuticals to benefit from the potential emerging technologies generated by Vertex.[3]

Explaining the observed variety of organization and financial structures of R&D activities requires

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[1] Day, Mang, Richter and Roberts," The innovative organization," The McKinsey Quarterly n.2, 2001.

[2] Quinn and Hilmer, "Make versus buy: Strategic outsourcing," The McKinsey Quarterly n. 1, 1995.

[3] Agarwal, Desai, Holcomb, and Oberoi, "Unlocking the value in Big Pharma," The McKinsey Quarterly n.2, 2001.

a better comprehension of the basic mechanisms that govern the economics and finance of innovation.[4] In modern economies, innovation and R&D may take place in a variety of organization and financial forms. These range from small "high-tech" boutiques financed by independent venture capital and/or the public equity market, to R&D divisions of large manufacturing firms. Also, new forms of organization of R&D have emerged in the recent years, where small specialized research firms reach agreements with large manufacturing companies that develop their research into finished products (see, for example, Robinson 2000). These agreements, which may take the form of corporate venture capital or "strategic alliances," offer a substitute to either independent venture capital or the direct integration of research units through mergers and acquisitions.[5] While considerable theoretical and empirical research has been devoted to understanding independent venture capital financing and IPOs,[6] there has been so far limited work on the basic economic and financial implications of strategic alliances and corporate venture capital.[7]

In this paper we propose an integrated framework where the organization and financing of R&D activities emerge as the equilibrium outcome of a R&D race. By explicitly modeling the choice of organization and financing of innovation activities in the context of a R&D race, we develop a unified theory of integration, venture capital financing and strategic alliances. In our paper, the organization and financing of innovation emerge as optimal responses to the competitive pressures of the R&D race, the reseach intensity of an R&D project, the stage of the research and product development, and the severity of financial

[4] Zingales (2000) gives an excellent discussion of the challenges faced by contemporary corporate finance in addressing these issues.

[5] "Strategic alliances" include a variety of different agreements in which two independent firms pool resources and capabilities to pursue a common goal. In this paper, we will focus on "research "alliances, in which the main focus of the alliance is the pursuit of an R&D project. Often, in such alliances, one party of the alliance (the "investor") finances most the necessary R&D expenditures incurred by the other party, in exchange for an equity position or as (partial) pre-payment of subsequent licencing fees (se, for example, Parise and Sasson, 2002, and Drzal, 2002).

[6] See, for example, Zingales (1995), Sahlman (1990), Gompers (1995), Gompers and Lerner (1999), Hellmann (1998, 2000), Repullo and Suarez (1998), Helmann and Puri (2000), Chemmanur and Fulghieri (1999), Kaplan and Stromberg (2000), Leshchinskii (2000), Casamatta (2001), Maksimovic and Pichler (2001), among others.

[7]A notable exception are Gompers and Lerner (1998) and Hellmann (2002).

constraints. Furthermore, in our model corporate venture capital and strategic alliances play a distinctive strategic role as an alternative to independent venture capital: Our paper offers a rational for the use of corporate venture capital and research alliances as strategic tools in R&D races.

We consider two firms that compete in a (downstream) output market and are engaged in a R&D race. Research is generated by each firm in collaboration with a research unit, which can either be integrated within the firm, as an "in-house" research division, or be set up as an external and independent upstream entity. Research is costly and requires the outlay of a certain fixed investment expenditure. The probability that research is successful, and thus leads to an innovation, depends on the (unobservable) level of effort exerted by both the research unit and the firm. If research is successful, the innovation is further developed by the firm into a marketable product. The payoff of the R&D cycle depends on whether one or both firms are successful, and on the level of competition in the product market.

In the spirit of Grossman and Hart (1986) and Hart and Moore (1990), in our model contracts are incomplete: research units and firms cannot contract ex-ante on the delivery of a certain innovation. The incomplete contracting framework is particularly appropriate in the R&D context because, by their very nature, innovation activities are difficult to define ex-ante, and therefore fundamentally uncontractible. When contracts are incomplete, a key feature is the ex-ante determination of the residual control rights, that is the allocation of the property rights of the innovation.

Thus, in our model firms and research units must decide on the allocation of the property rights of the innovation and the financing of the research activity. The firm and the research unit may decide to merge and integrate the research unit as one of the firm's internal divisions, in which case the property rights of the innovation are allocated to the firm. Alternatively, they may decide to remain as separate entities, in which case the research unit is an independent (upstream) entity, endowed with the full property rights of the innovation. Further, investment expenditures may be financed by the research unit directly, if it has sufficient amount of funds, by an independent venture capitalist, or by the firm. The choice of the property rights and the financing of the innovation is important because, by affecting the allocation of the surplus between the research unit and the firm, it influences the incentives to exert effort and thus the outcome of the R&D race.

We show that the choice of the organization structure (and the resulting allocation of the property rights) and the financing of innovation both play a strategic role in the R&D race. A firm can use the choice of organization and financial structure as a tool to secure a strategic advantage in the R&D race: the choice of organization and financial structure commits a firm and a research unit to accelerate their R&D activity (i.e. to exert more effort) with the goal of deterring their competitors in the race. Although such accelerated R&D activities are not optimal in a monopolistic setting, they become desirable when a firms and research units are engaged in a R&D race.

The choice of organization and financial structure depends also on the presence of financial constraints for the research unit. When the research unit is financially constrained, ex-ante bargaining between the firm and the research unit may not result in the choice of the organization structure that maximizes joint surplus. This happens because the research unit may not be able to compensate the firm in cases where the firm has the initial ownership of the innovation (or all the bargaining power) and the optimal organization structure involves the transfer of the ownership of the innovation to the research unit in exchange for a monetary payment.

The extent of financial constraints, however, may be mitigated by the ability of the research unit to raise capital by selling equity to an external, independent venture capitalist. Raising outside equity will allow the research unit to fund the fixed investment and possibly make a transfer payment to the firm. The disadvantage of such a strategy is that external financing by an independent venture capitalist dilutes the research unit's incentives to exert effort in the R&D race. The firm may therefore obtain a strategic advantage in the R&D race by providing direct financing to the research unit in the form of corporate venture capital or as a research alliance. Since the division of the surplus between the firm and the research unit is governed solely by the initial allocation of the property rights of the innovation, such source of financing has the advantage of not adversely affecting the research unit's incentives to exert effort. Thus, in our model corporate venture capital and research alliances emerge endogenously as a source of financing alternative to independent venture capital and as strategic tools in the R&D race.

The optimal organization and financial structure in our model is the result of the interaction of four underlying factors. The first factor is due to the impact of the allocation of property rights on the incentives to exert effort. As common in the incomplete contracting literature, this factor alone leads to an organization structure where the property rights of the innovation are allocated to the more productive party. The second factor is a cost sharing effect, and it captures the benefits of sharing knowledge and the costs of effort between the research unit and the firm. This factor favors organization structures where both parties have incentives to exert effort. The third factor is strategic in nature, and is due to the impact of the organization and financial structure on the equilibrium outcome of the R&D race. Since in our model research efforts exerted by the two competing firms are strategic substitutes, this factor favors organization and financial structures that accelerate a firm's research effort. The final factor is due to the presence of financial constraints and therefore the firms's ability to extract payments from the research unit. This factor would favor either an integrated organization structure, where the firm retains the ownership of the innovation, or a non integrated organization where the research unit raises funds from an external venture capitalist.

Our main results are summarized in Table III. For simplicity, we solve our model in two steps. We consider first the case in which both research units and their downstream firms are not subject to financial constraints. In this case, each research unit-firm team may achieve through bilateral bargaining and compensatory transfers the organization structure that maximizes joint surplus. We find that the research unit is more likely to be optimally integrated within the downstream firm when research intensity (proxied by research units' productivity) is low, R&D competition is stronger, and when the R&D race involves late-stage research. The research unit is instead more likely to be organized as a separate, independent company when research intensity is moderate to high, when R&D competition is weaker, or the research in the R&D cycle is early-stage research.

We examine next the effect of financial constraints, and we now assume that the research unit is, more realistically, financially constrained. We find that, when financial constraints are relevant, integration emerges also when the research intensity is moderate and is more likely when competition in the R&D race is more severe, or the R&D cycle involves late-stage research. If research intensity is sufficiently high, non-integration with financing by an independent venture capital emerges when the competition in the R&D race is less intense, or the R&D cycle involves early-stage research.

We find also that, as research intensity increases, the competition in the R&D race becomes stronger, or the R&D cycle involves more late-stage research, external financing by independent venture capital decreases and it is gradually replaced by corporate venture capital supplied by the downstream firm. Finally, if research intensity is sufficiently high and competition is sufficiently fierce, it becomes beneficial for the firm to unilaterally allocate the property rights of the innovation to the research unit and finance the investment expenditure by entering into a "strategic alliance" with the research unit.

Our paper is linked to a new, emerging stream of literature on the organizations structure of innovation activities. In a seminal paper, Aghion and Tirole (1994) examine the optimal organization structure between a research unit and a downstream firm, and they show that the ownership of innovation should be allocated to the more productive party in the relationship. While Aghion and Tirole's paper sheds important insights on the question of the optimal organization structure of innovation, it analyzes the optimal allocation of property rights of an innovation in isolation from the competitive conditions in the final output market. In reality, an important feature of R&D activities is that they are typically conducted within the context of a R&D race. Thus, the effect of competitive pressures exerted by R&D races on the ownership structure and financing of innovation remains an open issue. Robinson (2001) provides a model in which strategic alliances are used by companies' headquarters as a commitment device to overcome the adverse incentives of internal capital markets described in Stein (1997). Ambec and Poitevin (2000) examines the optimal organization structure of R&D in the presence of asymmetric information between a risk averse research unit and a downstream firm. Inderst and Mueller (2001) examine the impact of competition among venture capitalists on the outcome of their bargaining with entrepreneurs and on industry equilibrium. Finally, Casamatta (2001) examines the optimal financial contracts between an entrepreneur and a venture capitalist, where venture capitalists supply both funds and valuable advice.

Closer to our model, Bhattacharya and Chiesa (1995) examine the role of intermediaries (such as banks) as vehicles for sharing information between firms engaged in a R&D race. More recently, d'Aspermont, Bhattacharya and Gerard-Varet (2000) examine the problem of bargaining under asymmetric information over the licencing and transfer of information between two firms engaged in an R&D race. The main difference of our paper and theirs is that they assume the ownership structure and financing of the firms involved in the R&D race as given, and focus instead on the interim information sharing and its effects on ex-ante research incentives.

Our paper is organized as follows. In section 2, we outline the basic model. As a benchmark, in section 3, we consider the complete contracting case. In section 4, we examine the effect of competition in the R&D race on the choice of organization structure of two competing customer-research unit pairs in the absence of financial constraints. In section 5, we extend our basic model to examine the effects of financial constraints on the optimal organization and financial structure of competing pairs. Section 6 summarizes our major findings and offers some empirical predictions. Section 7 concludes.

2. The basic model

We consider two pairs of *research units* and their downstream firm, the *customers*, engaged in a R&D race. Research units undertake basic research which may lead to an innovation. Downstream customers complete the R&D process by developing the innovation into a product suitable for markets. For simplicity, we assume that each costumer is already paired at the beginning of the game with a research unit, and we study the game played by the two customer-research unit pairs competing in the R&D race.[8] We denote each customer-research unit pair with i, j = 1, 2.

We model the R&D race and the innovation process as taking place in two consecutive stages, which may be thought of as the steps necessary to complete a full R&D cycle. The first stage of the cycle, which we denote as the *research stage,* is mainly devoted to basic (or fundamental) research and is performed by the research unit in collaboration with the customer. The output of the research stage consists mainly in soft information, that is new knowledge in the form of an *innovation*. Even if the research stage is successful, the information produced at this stage (the innovation) is quite preliminary and is not sufficient by itself to obtain a final product directly exploitable in the product market.[9] To obtain a final, marketable product, the information produced at the research stage must be further elaborated in a second stage, which we denote as the *development stage*, executed by the customer.[10]

The entire R&D cycle is inherently risky. The outcome of the research stage may be either an innovation, *success*, or may result in no innovation, *failure*. The probability of success depends on the research activity, or *effort*, exerted by both the research unit and the customer. We denote the effort level provided by the research unit in pair i, i = 1,2, as e_i and the effort level provided by the customer as E_i. We can interpret research effort as the amount of knowledge that must be supplied as input of the research process which affects the probability of obtaining an innovation. Such knowledge may be provided by either the customer or the research unit, or both. Thus, the probability that the research stage successfully achieves an innovation, ϵ_i, is given by:

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[8] A more general model would examine the ex-ante matching of each research unit with a customer.

[9] In this paper, we assume that the research unit and the customer have already entered into an exclusive agreement, and they bargain in the interim over the licencing fee.

[10] Note that the product developed by the customer could be either a good for the final consumption or an intermediate good to be further processed before consumption.

$$\epsilon_i \equiv \Pr\{\text{Success}\} = \min\{\alpha e_i + E_i, 1\}, e_i \geq 0, E_i \geq 0, \quad i = 1, 2. \tag{2}$$

We characterize the marginal efficiency (productivity) of the research unit's effort relative to the customer's with the parameter α, with $0 \leq \alpha \leq \bar{\alpha}$. If $\alpha > 1$, the research unit is more productive than the customer in the research stage of the innovation process. Alternatively, if $\alpha < 1$, the customer is more productive than the research unit. The parameter α can be interpreted as measuring the degree of research intensity of a R&D project. Thus, high research intensive R&D projects in which the research unit is relatively more efficient are characterized by $\alpha > 1$. Conversely, less research intensive R&D projects in which the customer is relatively more efficient are characterized by $\alpha < 1$. Exerting effort is costly, representing the monetary and non monetary costs necessary to produce the knowledge required in the research stage. We assume that effort cost are convex: the cost for the research unit to produce one unit of effort is given by $\frac{1}{2}\kappa e^2$, with $\kappa \geq 1$; similarly, the cost for the customer to produce one unit of effort is $\frac{1}{2}\kappa E^2$. This cost convexity assumption captures the property that there may be benefits for the research unit and the customer from sharing knowledge at the research stage.

In addition to the individual effort levels (e, E), the research stage requires a certain (fixed) investment expenditure $K > 0$. This investment represents the monetary costs that must be borne in order to conduct the research activity in the first place. For simplicity, we assume that the level of investment is fixed, and that it does not affect the probability of success. Further, we assume that it is always optimal to sustain the investment expenditure K (that is, the full R&D cycle is a positive NPV project).

If the first research stage of the R&D cycle is successful, the customer must further develop the innovation before it can be transformed into a marketable product. The development stage is risky as well: it is successful with probability q and unsuccessful with the complement probability, $1 - q$. We interpret the parameter q as characterizing the type of research conducted in the R&D cycle. Early-stage research is intrinsically riskier, and is characterized by a lower probability of being successfully developed into a marketable product, and it has lower success probability q. Conversely, late-stage research is more likely to be successfully developed into a marketable product and has a higher success probability q. Thus, the parameter q measures how close the research object of the R&D cycle is to a final product.[11]

A critical feature of our model is that contracts are incomplete. We assume that the level of effort exerted by the research unit, e, and by the customer, E, are not contractible ex-ante. This assumption captures the notion that inputs of knowledge in the research stage are inherently not contractible between the two parties. Further, we also assume that contracts for the delivery of innovation cannot be designed and enforced. Since the output of the research stage is soft information, the two contracting parties are not able to enter ex-ante into a binding contract for the delivery of such innovation. The only possible ex-ante agreement between the customer and the research unit is the allocation of the property rights of the innovation. We consider two possible configurations of the property rights. In the first configuration, the research unit has full property rights of the innovation. This configuration may be interpreted as one in which the research unit is an independent entity, external to the customer. We denote this organization structure as the *non-integrated* case, N. In the second configuration of the ownership structure, the innovation is owned by the customer. This configuration may be interpreted as one in which the research unit is fully integrated within the customer, as one of its operational unit. We denote this organization structure as the *integrated* case, I. Finally, investment expenditures K are assumed to be contractible. If the non-integrated form is chosen, the research unit sustains the expenditure K. If instead the integrated form is chosen, expenditure K is borne by the customer.

The game unfolds as follows. We model the R&D race as a four-period game (see the time line in Table 1). In the first period (t = 1), denoted as the *organization choice* stage, each customer-research unit pair bargain and choose simultaneously the allocation of the property rights over the innovation, that is their

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[11] For example, a pharmaceutical research project devoted to the development of a new drug is substantially riskier and less likely to be successful when it is in pre-Phase I stage, and is characterized by a low value of q; conversely, the likelihood of obtaining a new marketable drug is higher when the project is during Phase III trials, which are characterized by a higher value of q.

organization form. That is, each pair chooses whether to engage in the R&D race as integrated (I) or non-integrated (N) pairs. An important feature of the model is that the optimal allocation of the property rights of the innovation between customers and research units may require the transfer of the ownership of the innovation from one party to the other, in exchange for a suitable monetary payment.[12] The possibility of such payment may be impaired by the fact that one of the bargaining parties has limited access to financial resources, making the transfer of the ownership of the innovation impossible. We initially assume that neither the customer nor the research unit are financially constrained. This implies that, given any initial allocation of bargaining power, each customer-research unit pair will achieve through bilateral bargaining and compensatory payments the organization form that maximizes total profits.

Given the allocation of property rights made in the first period of the game, in the second period of the game (t = 2), the *research* stage, each member of a customer-research unit pair chooses the level of effort (e, E) in the R&D race. Effort levels are chosen simultaneously by each pair, after observation of the organization structure chosen by the rival pair. Effort exerted by each pair determines the probability of success in the research stage according to Eq. (1).

The outcome of the initial research stage is known at time t = 3. If the research stage is successful, that is an innovation is obtained, in the third period of the game, the *bargaining* stage, the research unit and the customer bargain over the expected surplus that is generated in the subsequent development stage. The outcome of the bargaining process depends on the allocation of the property rights of the innovation chosen in the first stage of the game. If the research unit is integrated within the customer, the customer has the property rights of the innovation and will be able to exploit it commercially. Thus, in this case, the customer will be able to appropriate the entire surplus from the innovation. If, instead, the research unit is non-integrated, it has the property rights of the innovation. The research unit and the customer then bargain over

[12] Thus, such transfers can be interpreted as the proceeds from the sale the ownership (i.e. the residual rights) of the innovation.

the licencing fee, R, that the customer must pay to the research unit for the right to further develop and exploit the innovation commercially. For simplicity, we assume that in this case the research unit and the customer have the same bargaining power, and that they divide the expected surplus equally.[13] We assume also that, while the delivery of the innovation is not contractible, licencing fees and monetary transfers between the customer and the research unit are instead verifiable.

In the last period of the game (t = 4), the customer implements the second stage of the R&D process, the *development* stage. If this second stage is successful, the product is fully developed and ready for market. If instead the second stage is not successful, the project is abandoned and the customer earns zero profits. If successful, the payoff to a customer depends also on the success or failure of the rival pair engaged in the R&D race. We assume that if only one of the two customers is successful, it earns monopolistic profits, which, for notational simplicity, we normalize to 1. If, instead, both customers are successful, they compete in the output market and earn competitive profits $C \leq 1$. We assume that the level of competitive profits C measures the degree of competition in the output market between the two customers, which in turn depends on the degree of differentiation in the two product markets. Specifically, if the two customers have undifferentiated products and engage in Bertrand competition in the output market, we have C = 0. If instead the two product markets are perfectly segmented, each customer is able to earn the monopolistic profits, and we have that C = 1. In the intermediate cases of imperfect product differentiation and imperfectly competitive markets we have that $0 < C < 1$. Note that competitive losses occur only if both customers successfully complete the development stage, which happens with probability q^2. We denote the corresponding expected losses by $L \equiv q^2(1 - C)$. For a given probability of successful development q, these losses are lowest when there is no direct competition in the output market (when C =1), and are greatest when the competition fiercest (C = 0). Further, for a given level of competition C, expected losses are higher when

[13] Our analysis can be extended to accommodate alternative assumptions on the distribution of the bargaining power between customers and research units.

the success probability q is greater, that is when the R&D cycle involves more advanced stage research.

3. The complete contracting case.

We start our analysis by characterizing (as a benchmark) the first-best optimum that can be achieved when contracts are complete. In a first-best, the level of effort exerted by the research unit, e, and by the customer, E, and the nature of innovation are all fully contractible. Since in the first-best case the choice of organizational form is irrelevant, we need only to determine the equilibrium choice of effort exerted by the two competing customer-research unit pairs in the research stage of the game. Given the total probability of success at the research stage chosen by its competitor, ϵ_j, customer-research unit pair i chooses its effort levels (e_i, E_i) so as to maximize joint profits from innovation, π_T^{FB}, that is

$$\max_{\{e_i, E_i\}} \pi_T^{FB} = (\alpha\, e_i + E_i)(1 - \epsilon_j)\, q + (\alpha\, e_i + E_i)\, \epsilon_j\, (q - L) - \frac{\kappa}{2}\left(e_i^2 + E_i^2\right)$$

$$= (\alpha\, e_i + E_i)\left(q - L\, \epsilon_j\right) - \frac{\kappa}{2}\left(e_i^2 + E_i^2\right) \qquad \textbf{(2)}$$

$$\text{s.t. } \alpha\, e_i + E_i \leq 1\,, e_i \geq 0\,, E_i \geq 0\,.$$

We have the following Lemma.

***Lemma 1:* The optimal responses for a customer-research unit pair that correspond to the first-best problem (2) are given by:**

$$e_i^{FB}(\epsilon_j) = \frac{\alpha}{\kappa}\left(q - L\epsilon_j\right), \quad E_i^{FB}(\epsilon_j) = \frac{1}{\kappa}\left(q - L\epsilon_j\right), \quad \text{if } \frac{1+\alpha^2}{\kappa}\left(q - L\epsilon_j\right) < 1\,,$$

$$e_i^{FB}(\epsilon_j) = \frac{\alpha}{1+\alpha^2}, \qquad E_i^{FB}(\epsilon_j) = \frac{1}{1+\alpha^2}, \qquad \text{if } \frac{1+\alpha^2}{\kappa}\left(q - L\epsilon_j\right) \geq 1\,. \qquad \textbf{(3)}$$

Thus, the total probability of successfully completing the initial research stage that corresponds to the effort levels (3) is given by:

$$R_i^{FB}(\epsilon_j) \equiv \alpha\, e_i^{FB}(\epsilon_j) + E_i^{FB}(\epsilon_j) = \min\left\{ \frac{1+\alpha^2}{\kappa}\left(q - L\, \epsilon_j\right), 1 \right\}, \qquad \textbf{(4)}$$

and it represents the optimal combined response of a customer-research unit pair i, given a total probability of success of the rival pair ϵ_j. The Nash-equilibrium of the research stage is characterized in the following proposition.[14]

Proposition 1. (Complete contracting case) **In the case of complete contracting, the Nash-equilibrium levels of effort (e^{FB}, E^{FB}) at the research stage are given by :**

A) if $\frac{(1+\alpha^2)q}{\kappa + L(1+\alpha^2)} < 1$ and $\frac{1+\alpha^2}{\kappa} L < 1$:

$$e^{FB} = \frac{\alpha q}{\kappa + L(1+\alpha^2)}, \quad E^{FB} = \frac{q}{\kappa + L(1+\alpha^2)}, \quad \epsilon^{FB} = \frac{(1+\alpha^2)q}{\kappa + L(1+\alpha^2)}; \tag{5}$$

B) if $\frac{(1+\alpha^2)q}{\kappa + L(1+\alpha^2)} < 1$ and $\frac{1+\alpha^2}{\kappa} L \geq 1$:

$$e_1^{FB} = \frac{\alpha}{1+\alpha^2}, \quad E_1^{FB} = \frac{1}{1+\alpha^2}, \quad \epsilon_1^{FB} = 1,$$

$$e_2^{FB} = \min\{ \frac{\alpha(q-L)}{\kappa}; 1 \}, \quad E_2^{FB} = \frac{q-L}{\kappa}, \quad \epsilon_2^{FB} = \min\{ \frac{(1+\alpha^2)(q-L)}{\kappa}; 1 \}; \tag{6}$$

C) if $\frac{q(1+\alpha^2)}{\kappa + L(1+\alpha^2)} \geq 1$:

$$e^{FB} = \frac{\alpha}{1+\alpha^2}, \quad E^{FB} = \frac{1}{1+\alpha^2}, \quad \epsilon^{FB} = 1. \tag{7}$$

Proposition 1 characterizes the R&D race in the complete contracting case. The optimal allocation of research effort between customers and research units is uniquely determined by their relative productivity, α, and the benefits of sharing knowledge between them due to cost convexity. This beneficial effect of sharing knowledge may be detected by noting that when customers and research units are equally productive ($\alpha = 1$), the first best program requires equal effort allocation between them.

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[14] Note that we must account for the possibility that the symmetric Nash-equilibrium in the research stage is not stable. In this case, there are also two stable asymmetric Nash-equilibria, of which we choose the one with $\epsilon_1 = 1$ and $\epsilon_2 = R_2^{FB}(1)$.

The effect of competition between the two rival pairs on the research effort exerted in equilibrium (and on the total probability of success in the R&D race) can be seen by contrasting the competitive case of Proposition 1 with the case in which both rival pairs are effectively monopolists in their respective markets. This case corresponds in our model to a situation in which both customer-research unit pairs earn the monopolistic profits even if they are both successful in the R&D cycle, and it is obtained by setting C = 1. This implies that L = 0, and from Proposition 1, the optimal probability of success of the research stage in the complete contracting case under monopoly is given by

$$\epsilon^{M} \equiv \max \left\{ \frac{1 + \alpha^2}{\kappa} q , 1 \right\} . \qquad \textbf{(8)}$$

Comparing (8) with (5) - (7) reveals that the total probability of success will be higher under monopoly than in the competitive case, that is $\epsilon^{M} \geq \epsilon^{FB}$, for all (α, L). This implies that competition between the two rival pairs in the R&D race has the effect of reducing the total probability of success in the race. This property follows from the fact that competition between rival pairs decreases each pair's expected profits, leading to lower optimal effort. It can also be seen that this negative effect is more pronounced when the competition between rival pairs becomes more intense, that is the parameter C is lower, and R&D cycle involves late-stage research, that is the success probability q is higher.

4. Innovation and competition

When contracts are incomplete, the levels of research effort exerted by research units and customers are not contractible. In this case, customers and research units privately choose effort on the basis of their incentives. In turn, the allocation of the property rights of the innovation, by affecting the distribution of the joint surplus between research units and customers, will determine individual incentives. Thus, organizational form affects the level of effort that research units and customers are willing to exert in the research stage.

We now solve the model backward. We fist analyze the effort decision made by each customer-research unit pair. Given the organizational form chosen in the first period of the game, the two customer-research unit pairs determine simultaneously their respective levels of effort after observation of the organization structure chosen by the rival pair. Consider first the case of integration. If pair i has chosen the integrated form, the ownership of the innovation belongs to the customer. Thus, if the innovation process is successful, in the bargaining stage (t = 3) the customer appropriates all the expected value of the innovation and the research unit receives no payoff from the innovation process. Thus, the research unit exerts the minimal level of effort possible, which we normalize to zero (e = 0).[15] In this organization form, the customer captures the entire value of the innovation and fully internalizes costs and benefits from exerting effort at the research stage. Thus, given the rival pair's total effort ϵ_j, the customer of pair i chooses its level of effort E_i so as to maximize its expected profits,

$$\max_{E_i} \pi_C^I = E_i\left(q - L\epsilon_j\right) - \frac{\kappa}{2} E_i^2 , \qquad \text{s.t. } 0 \le E_i \le 1 . \tag{9}$$

The corresponding reaction function $R_i^I(\epsilon_j)$, and the total probability of success ϵ_i, are given by:

$$R_i^I(\epsilon_j) = \frac{q - L\epsilon_j}{\kappa} < 1 . \tag{10}$$

Consider now the case of non-integration. If pair i has chosen non-integration, the research unit has the ownership of the innovation. In this case, if the initial research stage is successful, in the third period of the game (t = 3) the research unit and the customer bargain over the licencing fees R that the customer must pay to the research unit to exploit the innovation commercially. The bargaining power of the research unit derives from the threat to exercise its ownership rights and withhold the innovation from the customer. Also, customers' revenues are verifiable, licencing agreements are contractible. Since, for simplicity, we assume

[15] Note that uncontractability of the delivery of innovation will also prevent the customer to design incentive contracts for the research unit that are contingent on the delivery of the innovation.

that research unit and customer have the same bargaining power, they split the net expected profits derived from the commercial exploitation of the innovation equally.

Incentives in the non-integrated and integrated organization form differ in an important way. Under integration, the customer has full ownership of the innovation and fully internalizes the returns of effort. In the non-integrated organization form, instead, the customer captures the value of the effort supplied only to the extent of its bargaining power in negotiations over the licensing fees R.[16] Similarly, the research unit must surrender some of the value created in the research phase to the customer, reducing its incentives to exert effort.

The optimal amount of effort levels exerted by research units and customers are determined as follows. Given the total level of effort ϵ_j chosen by then rival pair j, the levels of effort (e_i, E_i) chosen by the customer and research unit of pair i solve

$$\max_{e_i} \pi_{RU}^N = (\alpha e_i + E_i) \frac{1}{2} \left(q - L \epsilon_j\right) - \frac{\kappa}{2} e_i^2$$
$$\text{s.t. } \alpha e_i + E_i \leq 1, e_i \geq 0, \tag{11}$$

for the research unit, and

$$\max_{E_i} \pi_{C}^N = (\alpha e_i + E_i) \frac{1}{2} \left(q - L \epsilon_j\right) - \frac{\kappa}{2} E_i^2$$
$$\text{s.t. } 0 \leq \alpha e_i + E_i \leq 1, E_i \geq 0. \tag{12}$$

for the customer. We have the following.

***Lemma 2.* The optimal responses for a customer-research unit pair that correspond to the optimization problems (11) and (12) under non-integration are given, respectively, by:**

---

[16] Note that in this organization form, effort exerted by the customer, E, may be interpreted as consisting of all the preliminary knowledge transmitted to the research unit which increases the probability of obtaining a successful innovation. This knowledge may include, for example, detailed protocols or product specifications that may be needed by the customer in its downstream activity. Alternatively, the customer may dispatch some of its personnel to the research unit to collaborate in the research activity.

$$e_i^N(\epsilon_j) = \frac{\alpha}{2\kappa}\left(q - L\epsilon_j\right), \; E_i^N(\epsilon_j) = \frac{1}{2\kappa}\left(q - L\epsilon_j\right), \; \text{if } \frac{1+\alpha^2}{2\kappa}\left(q - L\epsilon_j\right) < 1,$$

$$e_i^N(\epsilon_j) = \frac{\alpha}{1+\alpha^2}, \qquad E_i^N(\epsilon_j) = \frac{1}{1+\alpha^2}, \qquad \text{if } \frac{1+\alpha^2}{2\kappa}\left(q - L\epsilon_j\right) \geq 1. \tag{13}$$

The total probability of success corresponding to the effort levels (13) is now

$$R_i^N(\epsilon_j) = \min\left\{\frac{1+\alpha^2}{2\kappa}\left(q - L\,\epsilon_j\right),\ 1\right\}. \tag{14}$$

It is important to note that, from Eq. (13) and Eq. (14), individual efforts (e_i, E_j) and the total probability $R_i^N(\epsilon_j)$ are a decreasing function of the rival pair's success probability ϵ_j.

The effect of the choice of organization structure on the success probability of a customer-research unit pair may be examined by the comparison of Eq. (10) and Eq. (14). In particular, it is easy to see that:

$$R_i^I(\epsilon_j) \geq R_i^N(\epsilon_j) \quad \text{iff} \quad \alpha \leq 1. \tag{15}$$

Eq. (15) reveals that the choice of organization form affects a pair's success probability in the R&D race (see Figure 1). Given the total success probability of pair j, ϵ_j, the effort levels chosen by pair i results in a greater success probability in the integrated form than in the non-integrated form if and only if the customer is relatively more productive than the research unit, that is $\alpha < 1$. When the customer is relatively more productive than the research unit, that is when $\alpha < 1$, a pair's reaction function under integration is to the right of the reaction function under non-integration; therefore, the choice of the integrated form makes the customer-research unit pair "more aggressive" in the R&D race than it would otherwise be if he had chosen the non-integrated form. Conversely, when the research unit is more productive, $\alpha > 1$, a customer-research unit pair is more aggressive in the R&D race in the non-integrated form of organization.

An important implication of Eq (15) is that the choice of organizational form, by affecting the optimal effort exerted by a customer-research unit pair in the research stage, has a strategic implication for the R&D race. Since research efforts exerted by the two competing firms are strategic substitutes, the overall effort chosen by a customer-research unit pair is a decreasing function of the rival pair's effort. Thus, by judicious choice of its organization structure, a customer-research unit pair can deter the rival pairs' research efforts by committing itself to a more aggressive posture in the R&D race. When a customer-research unit pair is a monopolist, there is no advantage by assuming a more aggressive posture in the R&D race. When, instead, a customer-research unit pair is engaged in a R&D race with another competing pair, it is beneficial to choose an organization structure that leads the pair to a more aggressive behavior in the race. This is the strategic effect of the ownership structure.

We now characterize the equilibrium of the R&D stage, given the preliminary choice of organization structure made by the two customer-research unit pairs. The ownership structure of the two customer-research unit pairs may be in one of three possible configurations: both research unit may be integrated with their customers (I-I case), they may be both non-integrated (N-N case), or one pair may be integrated, while the rival is non-integrated (N-I case) (the N-I case is discussed in the Appendix). Consider first the case in which both pairs have chosen an integrated organization structure. We have the following:

Lemma 3. **If both customer-research unit pairs are integrated, the Nash-equilibrium of the R&D race is given by:**

$$e^{I,I} = 0, \quad E^{I,I} = \epsilon^{I,I} = \frac{q}{\kappa + L}, \tag{16}$$

with corresponding equilibrium payoffs given by:

$$\pi_{RU}^{I,I} = 0, \quad \pi_{C}^{I,I} = \pi_{T}^{I,I} = \frac{\kappa q^2}{2(\kappa + L)^2}. \tag{17}$$

If both pairs have instead chosen the non-integrated organization structure, the Nash-equilibrium in R&D stage is characterized in the following lemma.[17]

---

[17] Note that in the case of non-integration we must again account for the possibility that the symmetric Nash-equilibrium is unstable. Also in this case, there are two stable asymmetric Nash-equilibria, of which we choose here the one with $\epsilon_1 = 1$ and $\epsilon_2 = R_2^N(1)$.

Lemma 4. **If both customer-research unit pairs are non-integrated, the Nash-equilibrium of the R&D race is given by:**

A) if $\dfrac{(1+\alpha^2)q}{2\kappa + L(1+\alpha^2)} < 1$ and $\dfrac{1+\alpha^2}{2\kappa}L < 1$:

$$e^{N,N} = \frac{\alpha q}{2\kappa + L(1+\alpha^2)}, \quad E^{N,N} = \frac{q}{2\kappa + L(1+\alpha^2)}, \quad \epsilon^{N,N} = \frac{(1+\alpha^2)q}{2\kappa + L(1+\alpha^2)}; \tag{18}$$

B) if $\dfrac{(1+\alpha^2)q}{2\kappa + L(1+\alpha^2)} < 1$ and $\dfrac{1+\alpha^2}{2\kappa}L \geq 1$:

$$e_1^{N,N} = \frac{\alpha}{1+\alpha^2}, \quad E_1^{N,N} = \frac{1}{1+\alpha^2}, \quad \epsilon_1^{N,N} = 1,$$

$$e_2^{N,N} = \min\{\frac{\alpha(q-L)}{2\kappa};1\}, \quad E_2^{N,N} = \frac{q-L}{2\kappa}, \quad \epsilon_2^{N,N} = \min\{\frac{(1+\alpha^2)(q-L)}{2\kappa};1\}; \tag{19}$$

C) if $\dfrac{(1+\alpha^2)q}{2\kappa + L(1+\alpha^2)} \geq 1$:

$$e^{N,N} = \frac{\alpha}{1+\alpha^2}, \quad E^{N,N} = \frac{1}{1+\alpha^2}, \quad \epsilon^{N,N} = 1. \tag{20}$$

The equilibrium payoffs in the non-integration case are displayed in Table 1. The effect of incomplete contracting on the equilibrium choice of effort can be detected by contrasting Lemma 3 and 4 with Proposition 1. It is easy to see that for all pairs (α,L) the overall equilibrium level of effort under incomplete contracting is lower than the one under complete contracts, for both the integrated and non integrated organization form. This is due to the fact that under incomplete contracts individual parties choose effort by maximizing their individual profits, which depend on their share of the total surplus, rather than the total surplus.

Consider now the first stage of the game, in which the two customer-research unit pairs choose their organizational form. The choice of organization form is made simultaneously at the beginning of the game, t = 1. With no financial constraints, the two pairs will chose the organizational form that maximizes the combined profits from the R&D race, that is the efficient organization structure. The equilibrium organization form depends on the productivity of the research unit relative to the customer, measured by the parameter α, and the amount of expected losses due to competition in the final output market, L, as follows.

Proposition 2. (Innovation and competition) **Under incomplete contracting and no financial constraints, the optimal organization structure is given by:**

i) for $\alpha < \sqrt{3}/3$ the optimal choice of organization is integration for all L;

ii) for $\sqrt{3}/3 \leq \alpha \leq 1$, there is a critical level $L_C(\alpha) \in [0, 1)$ such that both customer-research unit pairs choose the integrated form of organization if $L > L_C(\alpha)$ and they choose non-integration if $L \leq L_C(\alpha)$; furthermore, the critical level $L_C(\alpha)$ is an increasing function of α;

iii) for $\alpha > 1$, the optimal form of organization is non integration for all L.

The optimal choice of organization structure depends on the particular combination of the parameters (α, L). Note that expected losses L are affected by both the parameter C, measuring the degree of competitiveness of the output market, and the parameter q, measuring the degree of advancement of the research object of the R&D race. The effect of competition on the R&D race may be seen by contrasting again the competitive case of Proposition 2 with the case in which both customers earn, if successful, monopolistic rents, that is when C = 1. By setting L = 0 in Proposition 2, we obtain that the optimal organization structure under monopoly is as follows.

Proposition 3. (Optimal organization form under monopoly) **Under incomplete contracting and no financial constraints, the optimal organizational structure under monopoly is given by:**

i) the research unit is optimally integrated within the customer if $\alpha < \sqrt{3}/3$;

ii) the research unit is optimally non-integrated if $\alpha \geq \sqrt{3}/3$.

From Propositions 2 and 3 we can immediately see that the choice of organizational form is the same under competition and monopoly when $\alpha < \sqrt{3}/3$ and when $\alpha > 1$. In these cases the choice of organizational form is dictated solely by the relative productivity of the customer and the research unit, characterized by the parameter α. When $\alpha < \sqrt{3}/3$, the customer is sufficiently more productive relative to the research unit that integration is the optimal form of organization for all degrees of competition in the final output market, that is for all values of L. Conversely, when $\alpha \geq 1$, the research unit is more productive than the customer and the non-integrated organization form is optimal for all degrees of competition in the final output market.

When the relative productivity of the research unit is only moderately lower than the one of the customer, that is when $\sqrt{3}/3 \leq \alpha < 1$, the optimal form of organization depends on the productivity parameter α, the extent of competition C, and the success probability of the development stage q. We find that for any given level of the productivity parameter α, the integrated organizational form is more likely when competition on the final output market becomes more intense, that is when the parameter C is lower, and when the research activity in the R&D race is at more advanced stages, that is when the success probability of the development stage q increases. Given competition intensity, C, w also find that the non- integrated form becomes more desirable as the productivity of the research unit increases.

The reasons for these results are the following. In this region, the productivity of the research unit is only moderately lower than the one of the customer, and the choice of organization form depends on the interaction of two effects. The first is given by the benefits of knowledge sharing between customers and research units and it is due to the convexity of effort costs. In the integrated form, the research unit has no incentives to exert any effort, and the cost of producing innovation is entirely born by the customer. When the productivity of the research unit is sufficiently low (as it is when $\alpha < \sqrt{3}/3$), this organization form is optimal. In the non-integrated organization form the research unit receives a portion of the value of the innovation, and therefore it has an incentive to exert some effort. Convexity of the cost function thus makes the non-integrated form desirable because it allows a more effective allocation of effort between customer and research unit. This is the only effect in play under monopoly, making non-integration optimal also when the research unit is only moderately less productive than the customer, that is for $\sqrt{3}/3 \leq \alpha \leq 1$ (see Proposition 3).

The presence of competition in the R&D race adds a strategic consideration to the choice of the organization form. From Eq. (15) we know that when $\alpha < 1$ the total effort exerted by a customer-research unit pair, that is the total probability of success in the R&D race ϵ, is greater under integration than non-integration. Thus, when $\alpha < 1$, the choice of the integrated form provides a customer-research unit pair with a strategic advantage over its rival: it commits the pair to a more aggressive behavior in the R&D race, which in turn reduces the rival pair's effort. This strategic advantage increases the desirability of integration and it is more valuable when expected losses from competition are greater, that is when L is sufficiently large (that is, $L > L_C$). Thus, the integrated organization structure is more desirable when the competition in the output market is more intense, that is for lower values of C, or as the R&D cycle involves late-stage research, that is for higher values of the success probability q. Finally, we find that the critical value L_C increases with the productivity α. This implies that the optimal organizational form under competition becomes more similar to the monopolistic case as the productivity of the research unit increases. As the relative productivity of the research unit increases, the strategic advantage of integration is reduced. Thus, integration is optimal only when the extent of competition is the fiercest, that is for high values of expected competitive losses L.

5. Competition and the financing of innovation

When both the research unit and the customer are not subject to a financial constraint, they are able to achieve through bilateral bargaining the organization form which maximizes joint profits, B_T. The presence of financial constraints may prevent a customer-research unit pair to reach such an organization structure.[18] This possibility arises when a payment from one party to the other is required, and the presence of financial constraint impairs such payment. In this section, we assume that the research unit is more

[18] Lerner and Tsai (1999) document the cyclicality of external equity financing available to biotechnology firms, and the impact on the structure of research agreements with their downstream costumers.

realistically subject to a financial constraint, while the customer is not.[19]

In the presence of financial constraints, the ability of a customer-research unit pair to achieve the organization form maximizing joint profits depends on the initial distribution of the bargaining power. For simplicity, we assume that the party that has the ownership of the innovation at the initial stage also has the initial bargaining power. If the research unit has the initial ownership of the innovation (and the initial bargaining power) it will be able to extract through a payment from the customer all the gains that can be obtained from making the efficient choice of organization. Since the customer is not financially constrained, such a payment can occur. If the investment expenditure K is not too large, then the customer-research unit pair will be able to choose the organization form maximizing total profits for the pair. In this case, the outcome will be the same as the one discussed in the previous sections.

If the customer has the initial ownership of the innovation (and the initial bargaining power) in some cases the organization form maximizing total profits may not be reached. This happens when non-integration is the optimal form of organization. In this case, the choice of the non-integrated form requires the transfer of the ownership of innovation from the customer to the research unit. If the research unit is financially constrained, it may not be able to compensate the customer for the transfer of the innovation. The effect of this financial constraint is examined in this section.

We now assume that the customer has the initial ownership of the innovation and thus all the initial bargaining power, and that the research unit has zero initial wealth. At the beginning of the game, the customer decides the optimal organization form as follows. The first choice open to the customer is to maintain the ownership of the innovation and integrate the research unit as one of its divisions. In this case, the customer pays for the investment expenditure K. This choice generates exactly the same case as the integrated form discussed in the previous section.

[19] This assumption is consistent with the notion that the customer is large company with access to a deep pool of capital, while the research unit is a small organization with limited access to financial resources. In this paper, we do not model explicitly the origin of such financial constraints, but we assume their presence as exogenously given.

In alternative, the customer may transfer the ownership of the innovation to the research unit in exchange for a certain payment, T. If this option is chosen, the research unit must sustain the investment K. Given the presence of financial constraints, the research unit must raise the funds necessary to make the payment T to the customer and to pay for the investment K by selling equity to an external, independent venture capitalist. We denote this choice as *independent venture capital financing* (IVC). The difference with the model with no financial constraint is that now, if the customer has chosen the non-integrated form, selling equity in the private equity market dilutes the ownership of the research unit insiders' and therefore reduces the amount of effort exerted in equilibrium by the research unit.

The choice of the payment T that the customer requires from the research unit is made with the anticipation of the negative impact on the research unit's incentives. In fact, the negative impact on incentives may make it desirable for a customer to reduce the required payment T in order to reduce the amount of external equity raised by the research unit and thus restore its incentives. In some cases, the customer may be willing to offer a negative payment T, that is to subsidize the research unit. Such subsidy T, which we denote as *corporate venture capital* (CVC), reduces the need for the research unit to issue outside equity in the private equity markets to finance the investment expenditure K.[20] In extreme situations, it may even be desirable for a customer to set $T_i = - K$, that is to transfer the ownership of the innovation to the research unit at no cost, financing entirely the initial investment. We denote these arrangements as *strategic alliances* (S).

The main advantage of corporate venture capital and strategic alliances is that, contrary to independent venture capital, these form of financing do not have a negative impact on the research unit's incentives. This property depends on the fact that the division of the surplus between customers and research units is determined entirely by the initial allocation of the property rights of the innovation. Thus, corporate

[20]These transfers from the customers to the research unit may be interpreted either as an advance on future licencing fees, or as payments in exchange of an equity stake.

venture capital and research alliances emerge endogenously as a source of financing alternative to independent venture capital which can be used as a strategic tool in the R&D race.

The game now unfolds as follows. At the beginning of the game, t = 1, each customer chooses whether to maintain the ownership of the innovation and to integrate the research unit, or to transfer the ownership of the innovation to the research unit in exchange for a payment T_i, i = 1,2. In this latter case, research units sell a fraction of equity, $1 - \phi_i$, to independent venture capitalists in order to raise $T_i + K$ each. Each research unit retains a fraction of equity ϕ_i. The amount of external capital that the research unit must raise depends on payment T_i required by the customer and on the investment expenditure K.

At t = 2, each customer-research unit pair chooses the amount of effort to exert in the research stage of the game, as in the basic game, given the choice of organization structure and the fraction of external equity finance, $1- \phi_i$. After this, the game unfolds as before.

If both customers have chosen the integrated form, the Nash-equilibrium of the R&D race is given again by Lemma 3. If instead both customers have chosen in the first stage to transfer the ownership of the innovation to the research units, each research unit chooses the amount of effort to be exerted given the fraction of equity retained, ϕ_i. Thus, given the total level of effort ϵ_j chosen by the rival pair j, the levels of effort solve

$$\max_{e_i} \pi_{RU}^{\phi_i} = (\alpha e_i + E_i)\left(\frac{q}{2} - \frac{L}{2}\epsilon_j\right)\phi_i - \frac{\kappa}{2}e_i^2 \qquad \text{s.t. } 0 \leq \alpha e_i + E_i \leq 1, e_i \geq 0, \tag{21}$$

for the research unit, and

$$\max_{E_i} \pi_{C}^{\phi_i} = (\alpha e_i + E_i)\left(\frac{q}{2} - \frac{L}{2}\epsilon_j\right) - \frac{\kappa}{2}E_i^2 \qquad \text{s.t. } 0 \leq \alpha e_i + E_i \leq 1, E_i \geq 0, \tag{22}$$

for the customer. We have the following.

Lemma 5. **The reaction functions corresponding to the optimization problems (21) and (22) are given, respectively, by:**

$$
\begin{aligned}
&e_i^{\phi_i} = \frac{\alpha\,\phi_i}{2\kappa}\left(q - L\,\epsilon_j\right),\;\; E_i^{\phi_i} = \frac{1}{2\kappa}\left(q - L\epsilon_j\right),\;\; \text{if } \frac{1+\alpha^2\,\phi_i}{2\kappa}\left(q - L\epsilon_j\right) < 1\,,\\
&e_i^{\phi_i} = \frac{\alpha\,\phi_i}{1+\alpha^2\,\phi_i}\,, \qquad E_i^{\phi_i} = \frac{1}{1+\alpha^2\,\phi_i}\,, \qquad \text{if } \frac{1+\alpha^2\,\phi_i}{2\kappa}\left(q - L\epsilon_j\right) \geq 1\,.
\end{aligned}
\tag{23}
$$

The total probability of success corresponding to the effort levels (23) is now given by

$$
R_i^{\phi_i}(\epsilon_j) = \min\left\{ \frac{1+\phi_i\,\alpha^2}{2\kappa}\left(q - L\,\epsilon_j\right), 1 \right\}. \tag{24}
$$

By comparison of (10) and (24) we obtain that

$$
R_i^{I}(\epsilon_j) \geq R_i^{\phi_i}(\epsilon_j) \quad \text{iff} \quad \alpha\,\phi_i \leq 1\,. \tag{25}
$$

Equation (25) reveals that, similarly to our basic game, the choice of organizational form has again a strategic effect on the R&D race. By choosing the appropriate organization and financing forms, a customer-research unit pair can commit to a more aggressive posture in the R&D race. The difference with the basic case is that now the non-integrated organization will normally require some external finance from an independent venture capitalist. The presence of external finance has the effect of weakening the research unit's incentives to exert effort in the research stage. Thus, the presence of financial constraints, by reducing effort expended by the research unit, limits the strategic value of the non-integrated organization form.

Let $\{\epsilon_i(\phi_i;\phi_j),\epsilon_j(\phi_i;\phi_j)\}$ be the Nash-equilibrium of the research stage, given the amount of external financing 1- ϕ_i chosen in the financing game.[21] From (25) it is apparent that the equilibrium response of each customer-research unit pair is a decreasing function of the cost parameter κ. For simplicity, in the remainder of this section we assume that the parameter κ is sufficiently large that $\epsilon_i(\phi_i, \phi_j) < 1$ for all $(\phi_i, \phi_j) \in [0, 1]^2$, and that the corresponding symmetric Nash-equilibrium is stable. It is also easy to

[21]The Nash-equilibrium of the research stage is characterized in Lemma A1 in the Appendix.

verify that, as expected, the amount of total research effort exerted by pair i is an increasing function of the fraction of equity retained by the research unit, ϕ_i, and a decreasing function of the fraction of equity retained by the rival pair's research unit, ϕ_j, i,j = 1,2. Thus, the choice of the financing of innovation, by affecting the research unit's incentives to exert effort, has itself a strategic effect on the outcome of the R&D race and therefore a strategic value to the customer.

Consider now the choice of the payment, T_i, that a customer requires for the allocation of the property rights of the innovation to the research unit, if such organization structure is chosen. The choice of the amount of the payment T_i is made by the customer with the anticipation of the extent of venture capital financing $1 - \phi_i$ that is necessary to raise the required amount T_i and to pay the investment costs K. Thus, the pair $\{T_i, \phi_i\}$ is determined by maximizing the customer's total profit π_C^{ϕ}, that is:

$$\begin{aligned} &\max_{\{\phi_i, T_i\}} \pi_C^{\phi} = \epsilon_i(\phi_i,\phi_j)\left(\frac{q}{2} - \frac{L}{2}\epsilon_j(\phi_i,\phi_j)\right) + T_i - \frac{\kappa}{2}\left(E_i(\phi_i,\phi_j)\right)^2 \\ &\text{s.t. } T_i + K_i \leq \epsilon_i(\phi_i,\phi_j)\left(\frac{q}{2} - \frac{L}{2}\epsilon_j(\phi_i,\phi_j)\right)(1-\phi_i). \end{aligned} \qquad \textbf{(26)}$$

The optimal choice of the payment, T_i, and the fraction of equity retained, ϕ_i, are determined by the customer as the outcome of the trade-off of three effects. The first one is the incentive effect of financing, and it reflects the positive impact of equity retention ϕ_i on the research unit's effort choice, ϵ_i. All else equal, a greater equity retention ϕ_i leads to a higher effort from the research unit and thus to a greater success probability ϵ_i. This in turn benefits the customer directly, by increasing the expected value of its share of total surplus, and indirectly, by allowing the research unit to increase the share value of the equity it sells to the independent venture capitalist, and thus pay a larger payment T_i. The second effect is the strategic effect of financing, and it reflects the negative impact of retention ϕ_i on the rival pair's total effort ϵ_j that arises in the equilibrium of the R&D game. As in the previous case, all else equal this effect will benefit the customer directly, by increasing its share of the total expected surplus, and indirectly, by allowing a bigger payment. These two factors make a customer to prefer a higher retention rate ϕ_i. The third factor is the negative effect of the retention ϕ_i on the size of the payment T_i. This effect is due to the fact that increasing the research unit's equity retention ϕ_i limits, all else equal, the ability to raise funds from an external venture capitalist and thus reduces the size of the payment T_i. This *rent extraction* effect represents the cost of giving the research unit incentives through equity retention. The optimal payment T_i and the fraction of equity sold to a venture capitalist $1 - \phi_i$ are then determined by trading off the benefits of the strategic and incentive effects of equity retention against the disadvantage of a lower payment, T_i. We can now characterize the Nash-equilibrium of the financing subgame.

Proposition 4. (The financing of innovation) **The unique symmetric Nash-equilibrium (ϕ^*, ϕ^*) of the research unit financing stage is given by the following:**

$$
\begin{aligned}
&\text{(i)} && \phi^{N*} = 0 && \text{for } 0 \le \alpha \le \alpha_0(L)\,; \\
&\text{(ii)} && \phi^{N*} = \phi^N(\alpha, L) && \text{for } \alpha_0(L) < \alpha < \alpha_1(L); \\
&\text{(iii)} && \phi^{N*} = 1 && \text{for } \alpha \ge \alpha_1(L).
\end{aligned}
\tag{27}
$$

Furthermore, the thresholds levels $\alpha_0(L)$ and $\alpha_1(L)$ are decreasing functions of L.

The optimal amount of equity retention by the research unit, $\phi^N(\alpha, L)$ depends on both the productivity parameter α and the expected losses L as follows.

Proposition 5. (Comparative statics) **The equilibrium amount of equity retention by the research unit in the financing stage $\phi^N(\alpha, L)$ is an increasing function of both the research unit's productivity, α, and the expected competitive losses, L.**

The strategic implications of the financing of innovation may be seen by contrasting the competitive case of Proposition 4 with the corresponding monopolistic case, characterized in the following proposition.

Proposition 6. (The financing of innovation under monopoly) **Under monopoly, the customer will optimally finance the research unit as follows:**

$$
\begin{aligned}
&\text{(i)} && \phi^{M*} = 0 && \text{for } \alpha \le \sqrt{2}/2; \\
&\text{(ii)} && \phi^{M*} = \phi^M(\alpha) \equiv 1 - 1/2\alpha^2 < 1 && \text{for } \alpha > \sqrt{2}/2.
\end{aligned}
$$

Furthermore, $\partial \phi^{M}(\alpha)/\partial\alpha > 0$, and $\phi^{M}(\alpha) < \phi^{N}(\alpha, L)$ for $L > 0, \alpha > \sqrt{2}/2$.

The strategic role financing and the effect of competition on the choice of financing, are revealed by contrasting the competitive case of Proposition 4 with the monopolistic case of Proposition 6. Consider first the monopolistic case. When the productivity of the research unit is sufficiently low, that is $\alpha \le \sqrt{2}/2$, a monopolistic customer derives little benefits from promoting the research unit's effort through equity retention. In this case, the rent extraction effect dominates the incentive effect of financing and the customer prefers to increase the amount of the payment T_i by setting $\phi_i = 0$. At greater productivity levels, $\alpha > \sqrt{2}/2$, the monopolistic customer finds it desirable to ameliorate the research unit's incentives by promoting equity retention; thus $\phi_i > 0$. The optimal amount of equity retention ϕ_i is determined by trading off the benefits of retention and the corresponding reduction in payment T_i. It turns out that in our case, the incentive effect dominates the rent extraction effect, and the optimal retention ϕ_i is an increasing function of the research unit's productivity.

Consider now the competitive case of Proposition 4. When the productivity of the research unit is sufficiently low, that is for $\alpha \le \alpha_0(L=1)$, the choice of financing in the monopolistic and competitive cases coincide, with $\phi^* = 0$. In this range, research units have low productivity and equity incentives have little effect on a pair's success probability, with little benefit to customers. Thus, as in the monopolistic case, the rent extraction effect dominates the incentive effect, and the customer prefers a greater use of external venture capital financing, which allows a larger monetary payment T_i.

For $\alpha > \alpha_0(L)$, the optimal financing choices in the monopolistic and competitive cases, however, differ in some substantial ways. Specifically, we find that in the competitive case the customers will, in equilibrium, give the research units an equity stake ϕ_i which is greater (strictly greater for $\alpha > \sqrt{2}/2$) than the level under monopoly. The reason for the divergence between the monopolistic and the competitive cases is that, under competition, the choice of financing gives a customer an additional strategic advantage in the R&D race. By allowing the research unit to maintain a larger equity stake, and therefore by giving the research unit incentives to exert a greater effort, a customer will commit again the pair to a more aggressive posture in the R&D race. This financing choice will deter the rival pair from exerting research effort, and increase a pair's probability to pre-empt its rival in the R&D race. Thus, under competition, the optimal amount of external venture capital financing $1 - \phi_i$ is determined by customers by trading off the benefits of the incentive and strategic effects of giving high power incentives to the research unit against the financial gains from a greater payment T_i.

The optimal amount of equity retention $\phi^N(\alpha, L)$ depends on both the research unit's relative productivity, α, and expected competitive losses L (see Proposition 5). First, when the research unit is more productive, the benefits of improving incentives to exert effort are greater. Thus, the equilibrium amount of equity retention by the research unit, $\phi^N(\alpha,L)$, is an increasing function of the productivity of the research unit. Second, for a given level of research unit's productivity, α, the strategic benefits of financing will be larger when the expected competitive losses L are greater. Thus, the equilibrium equity stake of the research unit ϕ^N will be greater when the competition in the R&D race is more intense, or when the research is at a more advanced stage, that is probability q is greater.

Finally, when the research unit's productivity is sufficiently high, $\alpha > \alpha_1(L)$, the best strategy for customers is to maximize research units' effort by giving the research unit full equity ownership of the innovation and requiring no outside venture capital financing, that is setting* = 1. In this case, the payment T_i is negative and it is equal the monetary investment cost: $T_i = - K$. This is the case of a pure strategic alliance, in which the research unit has the full ownership of the innovation while the customer pays for the research cost K.

We can now examine the choice of organizational form made at the beginning of the game.

Proposition 7. (Ownership and financing of innovation) **Let $\kappa \geq \kappa_0$ (defined in the Appendix). Then, there are critical values $\{\alpha_I(L), \alpha_{I\phi}(L), \alpha_{\phi}(L), \alpha_S(L)\}$ such that:**

i) if $0 \leq \alpha \leq \alpha_I(L)$: both research units are integrated with their customers;

ii) if $\alpha_{I\phi}(L) \leq \alpha < \alpha_{\phi}(L)$: **one research unit is integrated with its customer, while its rival is non-integrated and is partially financed by an independent venture capitalist;**

ii) if $\alpha_{\phi}(L) \leq \alpha < \alpha_{S}(L)$: **both research units are non-integrated, and they are partially financed by independent venture capitalists;**

iii) if $\alpha_{S}(L) \leq \alpha \leq \bar{\alpha}$: **research units are non-integrated, and they are fully financed by their customers in a research alliance.**

Furthermore, $\partial \alpha_{I}(L)/\partial L > 0$ and $\partial \alpha_{S}(L)/\partial L < 0$.

Proposition 7 characterizes the equilibrium choice of the ownership and financing of innovation for the two rival pairs, and it is displayed in Figure 2 . The effect of the competitive pressure may again be assessed by contrasting the results of Proposition 7 with the monopolistic case, examined in the following proposition.

Proposition 8. (Ownership and financing under monopoly) **The optimal ownership structure and financing of innovation under monopoly is given by:**

i) the research unit is integrated within the customer if $\alpha < \sqrt{2}(1+\sqrt{5})/4$,

ii) the research unit is non integrated and partially financed by an independent venture capitalist if $\alpha \geq \sqrt{2}(1+\sqrt{5})/4$.

Several important observations arise from Proposition 7 and 8, and their comparison with the no financial constraint case examined in the previous section.

Consider first the monopolistic case, characterized in Propositions 3 and 8. In the absence of financial constraints (Proposition 3), we know that the optimal organization structure is integration when the productivity of the research unit is below the threshold level $\alpha = \sqrt{3}/3 < 1$, and non integration otherwise. The presence of a financial constraint has the effect of raising the threshold level after which a monopolistic customer prefers to allocate the ownership of the innovation to the productive research unit. If the research unit is financially constrained, it may not be able to fully compensate the customer for the transfer of the ownership of the innovation. The research unit partially pays for the transfer of the ownership of the innovation by selling equity to an independent venture capitalist, which in turn weakens its effort incentives. Thus, a monopolistic customer is willing to transfer the ownership of the innovation only at higher productivity levels of the research unit, that is for $\alpha \geq \sqrt{2}(1+\sqrt{5})/4 > 1 > \sqrt{3}/3$. Furthermore, the optimal fraction of equity retained by the research unit ϕ^{M*} is an increasing function of the research unit's productivity parameter α (Proposition 6).

Consider now the competitive case. In this case, the optimal organization structure depends on the interaction of the four effects discussed in this paper: the relative productivity of customers and research units, the benefits of knowledge sharing, the incentive and the strategic effects of the ownership and financing of the innovation, and the rent extraction effect. If the productivity of the research unit is sufficiently low, that is for $0 \leq \alpha \leq \alpha_I(L)$, the non-integrated structure provides little incentive and strategic benefits to the customer. Furthermore, in this region the research unit can raise only a limited amount of capital from external venture capitalists. Thus, the benefits to the customer from switching to the non-integrated organization structure are less than the loss from the transfer of the ownership of the innovation to the research unit, and the optimal organization form is integration.

The threshold level, $\alpha_I(L)$, depends on the intensity of the competition in the R&D race, and it derives from the trade-off of two effects. The first is the financial effect and it depends on the negative impact of the competitive pressure on the amount of external equity raised form venture capitalists, $1 - \phi_i$, and therefore the size of the payment T_i. The second is the strategic effect of transferring the innovation to the more productive research unit; this effect is more valuable to the customer when the competitive pressure is greater. As it turns out, in this region the first effect dominates, and increased competition makes the customer more likely to prefer integration. Integration will also be optimal when the research involved in the R&D cycle is late-stage research, that is when the parameter q is greater.

For greater levels of α, that is when $\alpha \geq \alpha_{\phi}(L)$, the productivity of the research unit is high enough to make non-integration the optimal organization form. Now the customer transfers the ownership of the innovation to the research unit, which in turn finances itself by selling equity to an independent venture capitalist. In this region, the productivity of the research unit is larger than the customer's and the incentive and the strategic effects make the non-integrated form desirable. The benefits of non-integration are however tempered by the fact that the fraction of equity optimally retained by the research unit is larger when the productivity parameter α is greater, and thus the payment T is lower.

When the productivity of the research unit is sufficiently large, or the R&D race is sufficiently competitive, that is when $\alpha_S(L) \leq \alpha \leq \bar{\alpha}$, customers will transfer the ownership of the innovation to the research unit at no charge and will pay for the investment K in the context of a strategic alliance. Thus strategic alliances emerge as optimal organizational structure when both the productivity level of the research unit and the degree of competition are the highest.

6. Empirical implications

In this paper we have examined the choice of the optimal ownership and financing of innovation in the context of an R&D race. We have shown that the optimal organization and financing of innovation in a competitive environment depends on both the productivity of a research unit relative to its customer, on the intensity of the R&D race, and on the availability of capital to the research unit. The optimal choice of organization and financing emerge as the outcome of the complex interaction of four main effects.

The first effect is the benefit of sharing the cost of knowledge production between the customer and the research unit, and is due to the convexity of cost structures. The second effect is an incentive effect, and it depends on the property that the organization and financial structure affects the distribution of the surplus between contracting parties and therefore their incentives to exert effort. All else equal, this effect favors integration when the customer is more productive than the research unit, and non-integration otherwise. In non-integrated structures, it also favors equity retention by the research unit, and therefore the use corporate venture capital and strategic alliances as a substitute for independent venture capital.

The third effect is given by the strategic implications of the ownership and financing of innovation. This effect derives from the strategic value that a customer-research unit pair obtains from choosing an ownership and financial structure that commits the pair to a more aggressive posture in the R&D race. This value is strategic in that it deters the rival pair in the race from exerting effort. This effect favors the organization structure which gives more incentives to the more productive party, and it is more critical when competition in the R&D race is more intense.

Finally, the fourth effect is due to the presence of financial constraints, which limit the ability of the customer to extract rents form the research unit and thus internalize the value of the innovation. This effect will favor integration, in which the customer maintains the ownership of the innovation and fully appropriates its value.

The interaction of these effects in our model allows to us to derive several empirical implications that are novel in the literature.

Implication 1 (Integration): *Integration is more likely to emerge when the customer is more productive than the research unit, and competition in the R&D race is more intense or the R&D cycle involves late-stage research, and when the research unit is financially constrained.*

Implication 2 (Non-integration): *Non-integration and venture capital financing is more likely to emerge when the research unit is more productive than the customer, when competition in the R&D race is less intense or the R&D cycle involves early-stage research, and when the research unit is not financially constrained.*

When the customer is more productive than the research unit, our model predicts that integration is more likely to occur when expected competitive losses are grater, that is when competition in the R&D race is more intense or the R&D cycle involves late-stage research. Conversely, when competition in the R&D race is moderate and the R&D cycle involves early-stage research, customer-research units are more likely to take advantage of the benefits of knowledge sharing offered by non-integrated organization structures, possibly financed by venture capital. These predictions are consistent with the findings in Robinson (2000), showing that mergers are more likely to occur in industries with more mature products and with more concentration. Further, when the research unit is financially constrained, integration occurs (inefficiently) even when the research unit is more productive than the customer. This prediction is consistent with the evidence described in Lerner and Merges (1998) and Lerner and Tsai (1999). These works show that the presence of financial constraints leads biotechnology firms to engage in research agreements which are more unfavorable to them and with poorer long term performance.

Implication 3 (Independent venture capital financing): *Independent venture capital financing, as a fraction of the research unit's equity, is greater when competition in the R&D race is less intense, the R&D cycle involves early stage research, and when the productivity of the research unit is lower.*

Implication 4 (Corporate venture capital and strategic alliances): *Corporate venture capital financing and strategic alliances are more likely to emerge when competition in the R&D race is more intense, the R&D cycle involves late-stage research, and when the productivity of the research unit is higher.*

In our model the extent of independent venture capital financing is given by the advantage of giving the research unit high power incentives, and its is linked to the intensity of the R&D race, the productivity of the research unit and the development stage of the research involved in the R&D cycle. When competition in the R&D race is more intense, a customer will benefit most from accelerating the race by giving high power incentive to the more productive research unit. This is achieved by entering with research unit into a research alliance or a corporate venture capital agreement. This prediction is consistent with the evidence presented in Robinson (2000), showing that research alliances are more likely in industries with low concentration and low brand equity. Also, Allen and Phillips (2000) show that strategic alliances and corporate venture capital are more valuable in R&D intensive industries, where they lead to increases in capital expenditures and industry adjusted operating cash flows.

Implication 5 (Stage of production development): *Venture capital financing and strategic alliances are more likely to emerge when the product development is at earlier stages. Integration is more likely to emerge when the product development is at later stages, and for more mature products.* Our model implies also that organization and financial structure is linked to the stage of product development. For products in their early stage of development or for newer products, competition is low and the probability of successfully obtaining a commercially viable final product is smaller. In these cases, our model predicts that non-integration and independent venture capital financing should emerge as the optimal organization and financial structures. Conversely, at later development stages or for more mature products, integration is more likely to emerge as an optimal organization structure.

7. Conclusions

In this paper we develop a unified theory of integration, venture capital financing and strategic alliances, where the organization and financial structure of innovation emerge as the optimal response to the competitive pressures of the R&D race, the stage of the research and product development, and the severity of the financial constraints. We have shown that integrated organization structures are more likely to emerge when the downstream firm is more productive than the research unit, competition in the R&D race is more intense or the R&D cycle involves late-stage research, and when the research unit is financially constrained. Conversely, non-integration and venture capital financing is more likely to emerge when the research unit is more productive than the customer, when competition in the R&D race is less intense or the R&D cycle involves early-stage research, and when the research unit is not financially constrained. Strategic alliances and corporate venture capital financing is more likely to emerge when competition in the R&D race is more intense, the R&D cycle involves late-stage research, and when the productivity of the research unit is higher. The model has also predictions on the amount of venture capital financing in relation to the intensity of competition in the R&D race and the stage of research and product development.

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Table 1: The sequence of events in the basic game

- **t = 1:** ***Organization choice stage***

  Each customer (C) and research unit (RU) pair chooses simultaneously their organization structure, that is whether to merge and integrate (I) the RU within the C, or to remain as separate, non integrated entities (N).

- **t = 2:** ***Research stage***

  After observing the rival pair's organization structure, each C and RU simultaneously choose their effort levels (e_i, E_i).

  The probability of successfully obtaining an innovation is $\epsilon_i \equiv \min \{\alpha\ e_i + E_i\ ;\ 1\}$.

- **t = 3:** ***Bargaining stage***

  If the research stage is successful, the C and RU bargain over the distribution of the expected surplus.

  If the RU is integrated within the customer (I), the customer extracts all the surplus.

  If the RU is non-integrated (N), the research unit and the customer choose a licencing fee that splits the expected surplus equally.

- **t = 4:** ***Development stage***

  The C develops the innovation into a final product. The development stage is successful with probability q.

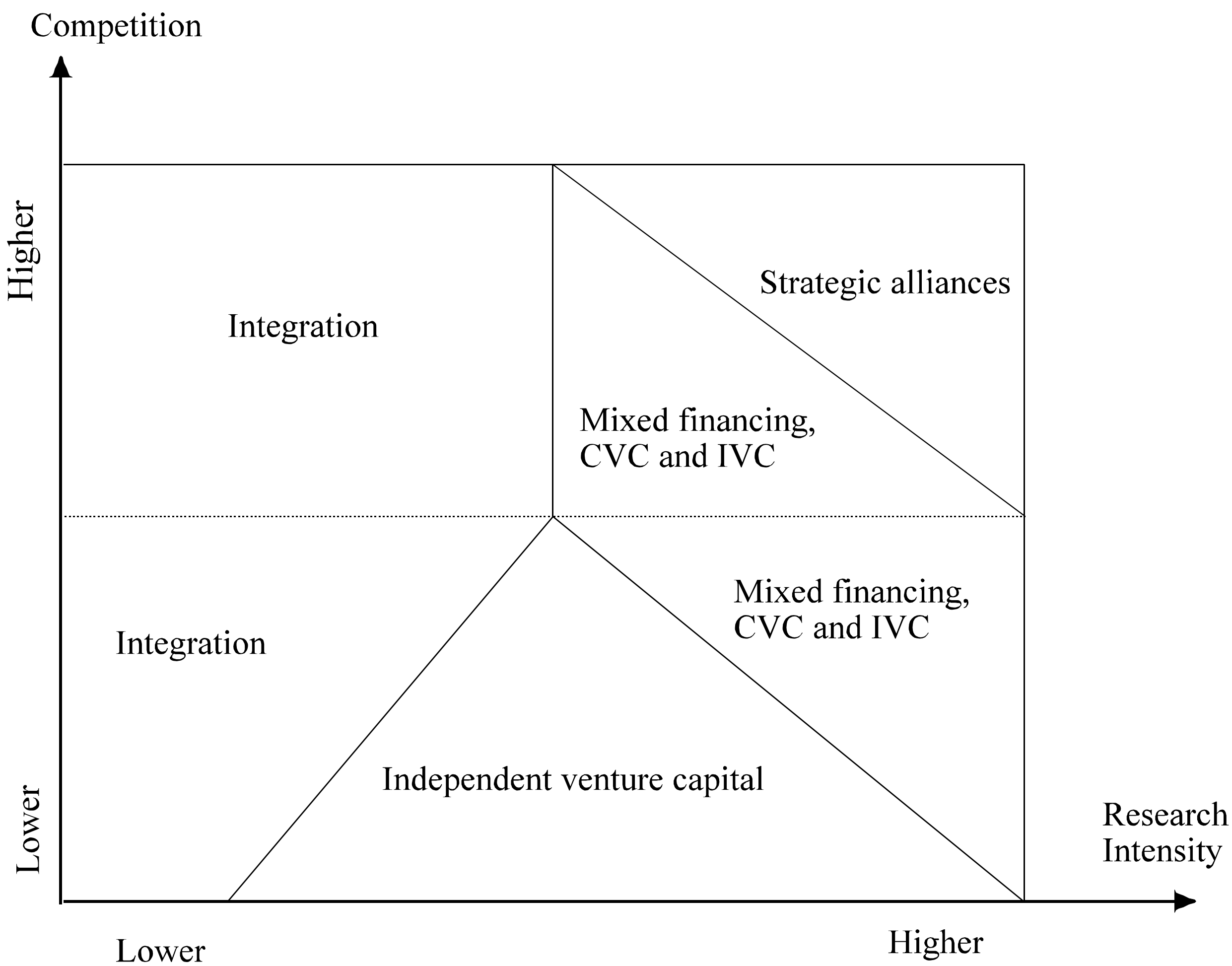
  If only one RU-C pair successfully develops the final product, the customer of the successful pair earns monopolistic profit equal to 1.

  If both rival pairs successfully develop the final product, each customer earn competitive profit $C \in [0, 1]$.

Table II: Profits under Competition: the case of Non-integration

if $(1+\alpha^2)L/2 \le \kappa^2$	
$\frac{q(1+\alpha^2)}{2\kappa + L(1+\alpha^2)} \le 1$	$\frac{q(1+\alpha^2)}{2\kappa + L(1+\alpha^2)} > 1$
$\pi_{RU}^N = \frac{\kappa q^2(2+\alpha^2)}{2\left[2\kappa + L(1+\alpha^2)\right]^2}$	$\pi_{RU}^N = \frac{q-L}{2} - \frac{\kappa\alpha^2}{2(1+\alpha^2)^2}$
$\pi_C^N = \frac{\kappa q^2(1+2\alpha^2)}{2\left[2\kappa + L(1+\alpha^2)\right]^2}$	$\pi_C^N = \frac{q-L}{2} - \frac{\kappa}{2(1+\alpha^2)^2}$
$\pi_T^N = \frac{3\kappa q^2(1+\alpha^2)}{\left[2\kappa + L(1+\alpha^2)\right]^2}$	$\pi_T^N = q - L - \frac{\kappa}{2(1+\alpha^2)}$
if $(1+\alpha^2)L/2 > \kappa^2$	
$\frac{(1+\alpha^2)q}{2\kappa + L(1+\alpha^2)} \le 1$	$\frac{(1+\alpha^2)q}{2\kappa + L(1+\alpha^2)} > 1$
$\pi_{RU}^N = \frac{q}{2} - \frac{(1+\alpha^2)L(q-L)}{4\kappa} - \frac{\kappa\alpha^2}{2(1+\alpha^2)^2}$	$\pi_{RU}^N = \frac{q-L}{2} - \frac{\kappa\alpha^2}{2(1+\alpha^2)^2}$
$\pi_C^N = \frac{q}{2} - \frac{(1+\alpha^2)L(q-L)}{4\kappa} - \frac{\kappa}{2(1+\alpha^2)^2}$	$\pi_C^N = \frac{q-L}{2} - \frac{\kappa}{2(1+\alpha^2)^2}$
$\pi_T^N = q - \frac{(1+\alpha^2)L(q-L)}{2\kappa} - \frac{\kappa}{2(1+\alpha^2)}$	$\pi_T^N = q - L - \frac{\kappa}{2(1+\alpha^2)}$

Table III : Summary of main results.



APPENDIX

Proof of Lemma 1. Consider the first-best problem (2). An effort pair (e,E) with either e = 0 or E = 0 is clearly not optimal. Consider then remaining the Kuhn-Tucker conditions for an optimum, where y is a Lagrangean multiplier:

$$\alpha(q - \epsilon_j L) - \kappa e - \alpha y = 0, \quad q - \epsilon_j L - \kappa E - y = 0, \quad y(1 - \alpha e - E) = 0, \quad \alpha e + E \leq 1. \qquad \textbf{(A1)}$$

Direct calculation shows that the triplet { $y = 0$, $e_i = \alpha(q - \epsilon_j L)/\kappa$, $E_i = (q - \epsilon_j L)/\kappa$ } is a solution to (A1) if and only if $(1 + \alpha^2)(q - \epsilon_j L)/\kappa < 1$. If $(1 + \alpha^2)(q - \epsilon_j L)/\kappa \geq 1$, then the solution is { $y = q - \epsilon_j L - \kappa/(1 + \alpha^2)$, $E = 1/(1 + \alpha^2)$; $e = \alpha/(1 + \alpha^2)$ }. ∎

Proof of Proposition 1. The determination of equilibrium values (e, E) must account for the fact that under some parameter values the symmetric Nash-equilibrium of the effort game is not stable, which happens when $(1 + \alpha^2)L/2\kappa \geq 1$. Consider first, from (4), the solution to $\epsilon = (1 + \alpha^2)[q - L\epsilon]/\kappa$, which is given by $\epsilon_X \equiv q(1 + \alpha^2)/[\kappa + (1 + \alpha^2)L]$. There are now three possible cases.

Case A: if $q(1 + \alpha^2)/[\kappa + (1 + \alpha^2)L] < 1$ and $(1 + \alpha^2)L/\kappa < 1$, then $\epsilon_X < 1$ and the symmetric Nash-equilibrium of the effort subgame is stable. In this case, direct substitution of ϵ_X into (3) yields (5).

Case B: if $q(1 + \alpha^2)/[\kappa + (1 + \alpha^2)L] < 1$ and $(1 + \alpha^2)L/\kappa \geq 1$, then $\epsilon_X < 1$, but the symmetric Nash-equilibrium of the effort subgame is not stable. In this case, we focus on the stable asymmetric Nash-equilibrium with $\epsilon_1 = 1$ and, from (4), with $\epsilon_2 = R^{FB}(\epsilon_1 = 1)$. Substitution into (3) yields (6).

Case C: if $q(1 + \alpha^2)/[\kappa + (1 + \alpha^2)L] \geq 1$, then $\epsilon_X \geq 1$; thus, from (4), set $\epsilon^{FB} = 1$, which, after substitution into (3), gives (7). ∎

Proof of Lemma 2. Following an argument similar to the one adopted in the proof of Lemma 1, we have that the first order conditions of the unconstrained version of problems (11) and (12) are $e_i = \alpha(q - L\epsilon_j)/2\kappa$ and $E_i = [q - L\epsilon_j]/2\kappa$, respectively. If $(1 + \alpha^2)(q - L\epsilon_j)/2\kappa < 1$, they satisfy (1), and they are also the unique solutions to (11) and (12). If instead $(1 + \alpha^2)(q - L\epsilon_j)/2\kappa \geq 1$, then there may be multiple pairs (e_i, E_i) solving (11) and (12). In this case, we choose the solution which maximizes total profits, $\pi_T^{C,N}$, giving the second line of equation (13). ∎

Proof of Lemma 3. The equilibrium value of $\epsilon^{I,I}$ is obtained by setting, from the reaction function equation (10), $\epsilon = (q - L)\epsilon/\kappa$, and solving for ϵ. The corresponding total profits are obtained by direct substitution of this value into (9). ∎

Proof of Lemma 4. The determination of equilibrium values of e and E under non-integration must account for the fact that, under some parameter values, the symmetric Nash-equilibrium of the effort game is not stable, which happens when $(1+\alpha^2)L/2\kappa \geq 1$. Consider first, from (18), the solution to $\epsilon = (1+\alpha^2)(q - L\epsilon]/2\kappa$, which is given by $\epsilon_Z \equiv q(1+\alpha^2)/[2\kappa + L(1+\alpha^2)]$. There are now three possible cases.

Case A: if $q(1+\alpha^2)/[2\kappa + L(1+\alpha^2)] < 1$ and $(1+\alpha^2)L/2\kappa < 1$, then $\epsilon_Z < 1$ and the symmetric Nash-equilibrium of the effort subgame is stable. In this case, direct substitution of ϵ_Z into (13) yields (18).

Case B: if $q(1+\alpha^2)/[2\kappa + L(1+\alpha^2)] < 1$ and $(1+\alpha^2)L/2\kappa \geq 1$, then $\epsilon_Z < 1$, but the symmetric Nash-equilibrium of the effort subgame is not stable. In this case, we focus on the stable asymmetric Nash-equilibrium with $\epsilon_1 = 1$ and, from (14), with $\epsilon_2 = R^N(\epsilon_1 = 1)$. Substitution in (13) yields (19).

Case C: if $q(1+\alpha^2)/[2\kappa + L(1+\alpha^2)] \geq 1$, then $\epsilon_Z \geq 1$; thus, from (20), $\epsilon^N = 1$, and, after substitution of into (13), we obtain (20). **9**

Proof of Proposition 2. For notational simplicity, in this proof we will define $S \equiv (1+\alpha^2)/2$. Consider the Nash-equilibrium of the effort choice subgame in the case in which in the first stage of the game one of the two customer-research unit pairs has chosen the integrated form, and the other pair has instead chosen the non-integrated form. Without loss of generality, we will denote as pair1 the customer-research unit pair choosing I, and as pair 2 the customer-research unit pair deviating and choosing N. We follow a procedure similar to the one adopted in the proof of lemma 4. From equations (16), (19) - (20), we have now that the Nash-equilibrium of the effort subgame is given by one of the following two cases:

Case (II-a): $SL^2 < \kappa^2$ and $q\,S(\kappa - L)/(\kappa - L^2S) < 1$:

$$e_1^{I,N} = 0, \qquad E_1^{I,N} = \frac{q(\kappa - LS)}{\kappa^2 - L^2S}, \quad \epsilon_1^{I,N} = \frac{q(\kappa - LS)}{\kappa^2 - L^2S}$$
$$e_2^{I,N} = \frac{q\alpha(\kappa - L)}{2\kappa^2 - 2L^2S}, \quad E_2^{I,N} = \frac{q(\kappa - L)}{2\kappa^2 - 2L^2S}, \quad \epsilon_2^{I,N} = \frac{qS(\kappa - L)}{\kappa^2 - L^2S} \tag{A2}$$

Case (II-b): $SL^2 \geq \kappa^2$ or $qS(\kappa - L)/(\kappa - L^2S) \geq 1$:

$$e_1^{I,N} = 0, \qquad E_1^{I,N} = \frac{q - L}{\kappa}, \quad \epsilon_1^{I,N} = \frac{q - L}{\kappa},$$
$$e_2^{I,N} = \frac{\alpha}{1+\alpha^2}, \quad E_2^{I,N} = \frac{1}{1+\alpha^2}, \quad \epsilon_2^{I,N} = 1\,. \tag{A3}$$

The corresponding equilibrium payoffs are displayed in Table A1. Note that we must again account for the possibility that the Nash-equilibrium is unstable, which now happens when $S L^2 \geq \kappa^2$. In this case, we focus again on the stable asymmetric Nash-equilibrium in which $\epsilon_2 = 1$.

Consider first the case of (I-I) equilibria. From our previous assumption, in this case the customer-research unit pair deviating from the candidate equilibrium is pair 2. Comparison of lemma 3 and equations (A2) and (A3) reveals that there are 2 separate cases.

Case (II-a): From Table A1, we have that (I, I) is an equilibrium if and only if

$$\pi_T^{I,I} \equiv \frac{\kappa q^2}{2(\kappa + L)^2} \geq \frac{3q^2\kappa(\kappa - L)^2 S}{4(\kappa^2 - L^2 S)^2} \equiv \pi_{T,2}^{I,N}. \qquad \textbf{(A4)}$$

By direct calculation, it may be verified that, for $S \leq 1$, inequality (A4) holds if and only if $L \geq L_I(S)$, where:

$$L_I(S) \equiv \left(\kappa^2 \frac{\sqrt{6S} - 2}{\sqrt{6S} - 2S}\right)^{\frac{1}{2}}. \qquad \textbf{(A5)}$$

Note that If $S > 1$, inequality (A4) never holds and (I,I) is never an equilibrium.

Case (II-b): Again from Table A1, we have that (I, I) is an equilibrium if and only if

$$\frac{\kappa q^2}{2(\kappa + L)^2} \geq q - \frac{L(q-L)}{\kappa} - \frac{\kappa}{4S}. \qquad \textbf{(A6)}$$

We will show that the inequality (A6) is never verified. Consider first the case where $L^2 S < \kappa^2$ and $qS(\kappa - L)/(\kappa^2 - L^2 S) \geq 1$. This implies that $[q(\kappa - L) + L^2]/4\kappa \geq \kappa/4S$, and that:

$$q - \frac{L(q-L)}{\kappa} - \frac{\kappa}{4S} \geq q - L(q-L) - \frac{q(\kappa - L) + L^2}{4\kappa} = \frac{3}{4}\left[\frac{q\kappa - L(q-L)}{\kappa}\right]. \qquad \textbf{(A7)}$$

Note next that $q - L(q - L) > q\kappa/(\kappa + L) > \kappa[q/(\kappa + L)]^2$ which implies that $3/4\,[q\kappa - L(q - L)]/\kappa > \frac{1}{2}\kappa\,[q/(\kappa + L)]^2$ violating (A6). Consider next the case in which $L^2 S \geq \kappa^2$. We have again that $q - L(q - L)/\kappa > q - L(q - L) > q\kappa/(\kappa + L)$; note next that $L < q < 1$ implies that $L^2/4\kappa < q\kappa/2(\kappa + L)$. Thus: $q - L(q - L) - L^2/4\kappa > q\kappa/(\kappa + L) - q\kappa/2(\kappa + L) = \frac{1}{2} q\kappa/(\kappa + L) > \frac{1}{2}\kappa[q/(\kappa + L)]^2$. Thus, $L^2 S \geq \kappa^2$ implies that $q - (L(q - L))/\kappa - \kappa/4S > q - L(q - L) - L^2/4\kappa > \frac{1}{2}\kappa[q/(\kappa + L)]^2$ violating again (A6).

We turn now to the (N-N) equilibria. In this case, the customer-research unit pair deviating from the candidate equilibrium is pair 1. From lemma 4 and equations (A2) and (A3) we can see that there are now 4 relevant cases, displayed in Figure A1.

Case (NN-a): $S L^2 < \kappa^2$ and $qS(\kappa - L)/(\kappa^2 - L^2S) < 1$. In this case, (N-N) is an equilibrium if and only if

$$\pi_T^{N,N} = \frac{3\kappa q^2 S}{(2\kappa + 2LS)^2} \geq \frac{\kappa q^2 (2\kappa - 2LS)^2}{2(2\kappa^2 - 2L^2 S)^2} = \pi_{T,1}^{I,N} . \tag{A8}$$

By direct calculation it is easy to verify that for $S \leq 1$ inequality (A8) holds if and only if $L \leq L_N(S)$, where

$$L_N(S) \equiv \left(\kappa^2 \frac{\sqrt{6S} - 2}{S(\sqrt{6S} - 2S)} \right)^{\frac{1}{2}} . \tag{A9}$$

Note that If $S > 1$, inequality (A9) always holds and (N,N) is always an equilibrium.

Case (NN-b): $LS < \kappa$, $qS(\kappa - L)/(\kappa^2 - L^2S) \geq 1$ and $qS/(\kappa + LS) < 1$. Now, (N-N) is an equilibrium if and only if

$$\frac{3\kappa q^2 S}{(2\kappa + 2LS)^2} \geq \frac{q^2(1 - L/q)^2}{2\kappa} . \tag{A10}$$

Note first that $qS/(\kappa + LS) < 1$ implies that $L/q > LS/(\kappa + LS)$. Note also that $qS(\kappa - L)/(\kappa^2 - L^2S) \geq 1$ implies that $S > 1$, which in turn implies that $[\kappa (3S/2)^{1/2} + L] / (\kappa + LS) > 1$. Thus, we have that $\kappa (3S/2)^{1/2} /(1 + LS) > 1 - L/q$, which, after squaring both sides and dividing by 2, implies (A10).

Case (NN-c): this case is composed of two subcases: (a) $qS/(\kappa + LS) \geq 1$ and $S L^2 \geq \kappa^2$, and (b) $qS/(\kappa + LS) \geq 1$ and $S L^2 < \kappa^2$. In both subcases (N,N) is an equilibrium if and only if

$$q - L - \frac{\kappa}{4S} \geq \frac{(q - L)^2}{2\kappa} . \tag{A11}$$

Nota that $qS/(\kappa + LS) \geq 1$ implies that $(q - L)/4 \geq \kappa/4S$. Thus, $q - L - \kappa/4s \geq 3(q - L)/4 \geq (q - L)^2/2 \geq (q - L)^2/2\kappa$, giving (A11). Thus, (N-N) is an equilibrium in both sub-cases.

Case (NN-d): This case is also composed of two subcases: (a) $qS/(\kappa + LS) < 1$ and $S L^2 \geq \kappa^2$, and (b) $qS/(\kappa + LS) < 1$ and $L^2S < \kappa^2 < L^2S^2$. In both cases, (N, N) is an equilibrium if and only if

$$q - \frac{SL(q - L)}{\kappa} - \frac{\kappa}{4S} \geq \frac{(q - L)^2}{2\kappa} . \tag{A12}$$

By direct calculation, we have that $q - (S L(q - L))/\kappa - \kappa/4S > 3S(q - L)^2/4\kappa$ when $L > (qS - \kappa)/S$, which is implied by $qS/(\kappa + LS) < 1$. $3S(q - L)^2/4\kappa > (q - L)^2/2\kappa$, for $S>2/3$. The latter inequality is always verified since $S L^2 \geq \kappa^2$ and $L^2S < \kappa^2 < L^2S^2$ both imply that $S \geq 1$ Thus, (N-N) is an equilibrium in both sub-cases.

Note now that $L_N(2/3) = L_I(2/3) = 0$, and that $L_N(1) = L_I(1) = \kappa$. Furthermore, it may be easily verified that $L_N(S)$ and $L_I(S)$ are both increasing and concave functions of S. Comparison of (A5) and (A9) reveals that $L_N(S) \geq L_I(S)$. Thus for all (S, L) such that $L_I(S) \leq L \leq L_N(S)$ both (I-I) and (N-N) equilibria exist. Finally, from (A4) and (A8) it may be verified that for $2/3 \leq S \leq 1$, we also have

$$\pi_T^{N,N} = \frac{3\kappa q^2 S}{(2\kappa + 2LS)^2} \geq \frac{\kappa q^2}{2(\kappa + L)^2} = \pi_T^{I,I} . \tag{A13}$$

and the (N-N) equilibrium Pareto-dominates. Thus, in the presence of multiple equilibria we will assume that both customer-research unit pairs will choose the Pareto-dominating (N-N) equilibrium. The proof is concluded by setting $L_C(\alpha) \equiv L_N[S(\alpha)]$. **9**

Proof of Proposition 3. If $(1 + \alpha^2)q/2\kappa < 1$, comparison of the total profits under integration and non-integration reveals that non-integration is optimal if and only if $2/3 \leq (1 + \alpha^2)/2 < 1$. If $(1 + \alpha^2)/2 > 1$, non-integration is always optimal. **9**

Proof of Lemma 5. The proof of this lemma follows the proof of Lemma 2, and is omitted. **9**

Proof of Proposition 4. To prove this proposition we need the following Lemma, which characterizes the Nash-equilibrium of the R&D race.

Lemma A1. **If both customer-research unit pairs are not integrated, the Nash-equilibrium of the R&D race is given by:**

1) if $\dfrac{(1+\alpha^2\phi_i)\,q\,[2\kappa - L(1+\alpha^2\phi_j)]}{4\kappa^2 - L^2(1+\alpha^2\phi_i)(1+\alpha^2\phi_j)} < 1$ for i, j and $\dfrac{L^2(1+\alpha^2\phi_i)(1+\alpha^2\phi_j)}{\kappa^2} < 4$:

$$e_i^{\phi_i,\phi_j} = \frac{\alpha\, q\, \phi_i[2\kappa - L(1+\alpha^2\phi_j)]}{4\kappa^2 - L^2(1+\alpha^2\phi_i)(1+\alpha^2\phi_j)}, \qquad E_i^{\phi_i,\phi_j} = \frac{q\,\phi_i[2\kappa - L(1+\alpha^2\phi_j)]}{4\kappa^2 - L^2(1+\alpha^2\phi_i)(1+\alpha^2\phi_j)},$$
$$\epsilon_i^{\phi_i,\phi_j} = \frac{(1+\alpha^2\phi_i)\,q\,[2\kappa - L(1+\alpha^2\phi_j)]}{4\kappa^2 - L^2(1+\alpha^2\phi_i)(1+\alpha^2\phi_j)}; \tag{A14}$$

2) if: (2-i) $\dfrac{(1+\alpha^2\phi_i)\,q\,[2\kappa - (1+\alpha^2\phi_j)]}{4\kappa^2 - L^2(1+\alpha^2\phi_i)(1+\alpha^2\phi_j)} < 1$ for i,j and $\dfrac{L^2(1+\alpha^2\phi_i)(1+\alpha^2\phi_j)}{\kappa^2} \geq 4$, **or**

(2-ii) $\dfrac{(1+\alpha^2\phi_2)\,q\,[2\kappa - L(1+\alpha^2\phi_1)]}{4\kappa^2 - L^2(1+\alpha^2\phi_1)(1+\alpha^2\phi_2)} \geq 1$ and $\dfrac{L^2(1+\alpha^2\phi_1)(1+\alpha^2\phi_2)}{\kappa^2} \geq 4$, **or**

(2-iii) $\dfrac{(1+\alpha^2\phi_1)\,q\,[2\kappa-(1+\alpha^2\phi_2)]}{4\kappa^2-L^2(1+\alpha^2\phi_1)(1+\alpha^2\phi_2)} \geq 1$ and $\dfrac{L^2(1+\alpha^2\phi_1)(1+\alpha^2\phi_2)}{\kappa^2} < 4$:

$$e_1^{\phi_1,\phi_2} = \frac{\alpha\,\phi_1}{1+\alpha^2\phi_1}, \quad E_1^{\phi_1,\phi_2} = \frac{1}{1+\alpha^2\phi_1}, \quad \epsilon_1^{\phi_1,\phi_2} = 1,$$

$$e_2^{\phi_1,\phi_2} = \frac{\alpha\,\phi_2\,(q-L)}{2\kappa}, \quad E_2^{\phi_1,\phi_2} = \frac{q-L}{2\kappa}, \quad \text{if } \epsilon_2^{\phi_1,\phi_2} = \min\left\{\frac{(1+\alpha^2\phi_2)(q-L)}{2\kappa};1\right\} < 1, \tag{A15}$$

$$e_2^{\phi_1,\phi_2} = \frac{\alpha\,\phi_2}{1+\alpha^2\phi_2}, \quad E_2^{\phi_1,\phi_2} = \frac{1}{1+\alpha^2\phi_2}, \quad \text{if } \epsilon_2^{\phi_1,\phi_2} = \min\left\{\frac{(1+\alpha^2\phi_2)(q-L)}{2\kappa};1\right\} = 1;$$

3) if $\dfrac{q(1+\alpha^2\phi_i)[2\kappa-L(1+\alpha^2\phi_j)]}{4\kappa^2-L^2(1+\alpha^2\phi_i)(1+\alpha^2\phi_j)} \geq 1$:

$$e_i^{\phi_i,\phi_j} = \frac{\alpha\,\phi_i}{1+\alpha^2\phi_i}, \quad E_i^{\phi_j,\phi_j} = \frac{1}{1+\alpha^2\phi_i}, \quad \epsilon_i^{\phi_i,\phi_j} = 1; \tag{A16}$$

4) if: (4-i) $\dfrac{(1+\alpha^2\phi_2)\,q\,[2\kappa-(1+\alpha^2\phi_1)]}{4\kappa^2-L^2(1+\alpha^2\phi_1)(1+\alpha^2\phi_2)} \geq 1$ and $\dfrac{L^2(1+\alpha^2\phi_1)(1+\alpha^2\phi_2)}{\kappa^2} < 4$, or

(4-ii) $\dfrac{(1+\alpha^2\phi_1)\,q\,[2\kappa-(1+\alpha^2\phi_2)]}{4\kappa^2-L^2(1+\alpha^2\phi_1)(1+\alpha^2\phi_2)} \geq 1$ and $\dfrac{L^2(1+\alpha^2\phi_1)(1+\alpha^2\phi_2)}{\kappa^2} \geq 4$:

$$e_2^{\phi_1,\phi_2} = \frac{\alpha\,\phi_2}{1+\alpha^2\phi_2}, \quad E_2^{\phi_1,\phi_2} = \frac{1}{1+\alpha^2\phi_2}, \quad \epsilon_2^{\phi_1,\phi_2} = 1,$$

$$e_1^{\phi_1,\phi_2} = \frac{\alpha\,\phi_1\,(q-L)}{2\kappa}, \quad E_1^{\phi_1,\phi_2} = \frac{q-L}{2\kappa}, \quad \text{if } \epsilon_1^{\phi_1,\phi_2} = \min\left\{\frac{(1+\alpha^2\phi_1)(q-L)}{2\kappa};1\right\} < 1, \tag{A17}$$

$$e_1^{\phi_1,\phi_2} = \frac{\alpha\,\phi_1}{1+\alpha^2\phi_1}, \quad E_1^{\phi_1,\phi_2} = \frac{1}{1+\alpha^2\phi_1}, \quad \text{if } \epsilon_1^{\phi_1,\phi_2} = \min\left\{\frac{(1+\alpha^2\phi_1)(q-L)}{2\kappa};1\right\} = 1.$$

Proof of Lemma A1. Define $\{\epsilon_{Yi}(\phi_i,\phi_j)\ \epsilon_{Yj}(\phi_i,\phi_j)\}$ as the (unique) solution to

$$\epsilon_i = \frac{1+\phi_i\alpha^2}{2\kappa}\left(q-L\,\epsilon_j\right), \quad \epsilon_j = \frac{1+\phi_j\alpha^2}{2\kappa}\left(q-L\,\epsilon_i\right), \tag{A18}$$

which is given by

$$\epsilon_{Yi}(\phi_i, \phi_j) = \frac{(1+\alpha^2\phi_i)\,q\,[2\kappa - L(1+\alpha^2\phi_j)]}{4\kappa^2 - L^2(1+\alpha^2\phi_i)(1+\alpha^2\phi_j)}\,. \qquad \textbf{(A19)}$$

The proof of this Lemma follows the same procedure of the proof of Lemma 4. We have now the following four cases.

Case 1: In this case, $\epsilon_{Yi} < 1$ and $\epsilon_{Yj} < 1$ and the symmetric Nash-equilibrium of the effort subgame is stable. Thus, direct substitution of ϵ_{Yj} into (23) yields $\epsilon_1 = \epsilon_{Y1}$ and $\epsilon_2 = \epsilon_{Y2}$, giving (A14).

Case 2-i: In this case $\epsilon_{Yi} < 1$, i = 1,2, but the symmetric Nash-equilibrium of the effort subgame is not stable. As before, we focus on the stable asymmetric Nash-equilibrium with $\epsilon_1 = 1$ and, with $\epsilon_2 = R_2^{\phi_2}(\epsilon_1 = 1)$. This gives (A15).

Case 2-ii: In this case, we have $\epsilon_{Y2} > 1$ and $L^2(1+\alpha^2\phi_1)(1+\alpha^2\phi_2) \geq 4\kappa^2$, and the unique (stable) equilibrium is obtained by setting $\epsilon_1 = 1$ and, $\epsilon_2 = R_2^{\phi_2}(\epsilon_1 = 1)$, giving again (A15).

Case 2-iii: In this case $\epsilon_{Y1} > 1$ and $L^2(1+\alpha^2\phi_1)(1+\alpha^2\phi_2) < 4\kappa^2$. Thus, we set $\epsilon_1 = 1$ and correspondingly $\epsilon_2 = R_2^{\phi_2}(\epsilon_1 = 1)$, which again gives (A15).

Case 3: In this case we have that $\epsilon_{Yi} \geq 1$, i = 1,2; thus, we set $\epsilon_1^{\phi} = 1$, giving (A16).

Case 4-i: In this case $\epsilon_{Y2} > 1$ and $L^2(1+\alpha^2 N_1)(1+\alpha^2 N_2) < 4\kappa^2$. From (23), we set $\epsilon_2^N = 1$ and $\epsilon_1 = R_1^{\phi_1}(\epsilon_2 = 1)$, which gives (A17).

Case 4-ii: In this case we have that $\epsilon_{Y1} > 1$ and $L^2(1+\alpha^2\phi_1)(1+\alpha^2\phi_2) \geq 4^2$, and the unique (stable) equilibrium is obtained by setting $\epsilon_2 = 1$ and, $\epsilon_1 = R_1^{\phi_1}(\epsilon_2 = 1)$, giving again (A17). □

We can now proceed to the proof of Proposition 4. In this proof, we assume that κ is sufficiently large so that $\epsilon_{Yi} < 1$, for i,j = 1,2. Thus, Case 1 in Lemma A4 apply. Consider next problem (26). It is easy to verify that the constraint of problem (26) will always be binding at an optimum (for a given ϕ_i, it will always be optimal to set T_i to satisfy the constraint as an equality). After substitution of the constraint, we obtain that the first-order condition of this problem, when the equilibrium of the R&D stage is in Case 1 of Lemma A1, give the system of equations.:

$$\phi_1 = \frac{L^2(1+\alpha^2\phi_2)(1+\alpha^2) + 4\kappa^2(2\alpha^2-1)}{\alpha^2[8\kappa^2 - (1+\alpha^2\phi_2)(1+2\alpha^2)L^2]}\,,\ \phi_2 = \frac{L^2(1+\alpha^2\phi_1)(1+\alpha^2) + 4\kappa^2(2\alpha^2-1)}{\alpha^2[8\kappa^2 - (1+\alpha^2\phi_1)(1+2\alpha^2)L^2]}\,. \qquad \textbf{(A21)}$$

Let $\{\phi^{N1}, \phi^{N2}\}$, $\phi^{N1} < \phi^{N2}$, the solutions to (A20), if they exist. Set $\phi^N \equiv \phi^{N1}$, where

$$\phi^N(\alpha, L) \equiv \frac{8\kappa^2 - L^2(3\alpha^2+2) - \sqrt{64\kappa 4 + L^2[\alpha^4 L^2 - 16\kappa^2(4\alpha^4 + 3\alpha^2 + 1)]}}{2\alpha^2(1+2\alpha^2)L^2}\,, \qquad \textbf{(A22)}$$

for L > 0, and $\phi^N \equiv (2\alpha^2 - 1)/2\alpha^2$ for L = 0. Let first $\phi^N \leq 0$. From the definition of ϕ^N, it may easily be seen that $\partial \pi_C^{\phi}(\phi_i, 0)/\partial \phi_i < 0$ for all $\phi_i \in [0, 1]$, for i, j = 1,2. Thus, the Nash-equilibrium of the financing stage is (0,0). Solving $\phi^N(\alpha, L) = 0$ for L we obtain that $\phi^N \leq 0$ for $L \leq L_{0N}(\alpha)$, where:

$$L_{0N}(\alpha) \equiv \frac{2\kappa}{1+\alpha^2}\sqrt{(1+\alpha^2)(1-2\alpha^2)}. \tag{A23}$$

Define then $\alpha_{0N}(L)$ as the inverse function of $L_{0N}(\alpha)$. It is easy to verify that $L_{0N}(\sqrt{2}/2) = 0$ and that $\alpha_{0N}(L)$ is a decreasing function of α. Let now $0 < \phi^N \leq 1$. From the definition of ϕ^N, we know that ϕ^N is a global maximum of $\pi_C^{\phi}(\phi_i; \phi^N)$ for all $\phi_i \in [0, 1]$. Thus, the pair $\{\phi^N, \phi^N\}$ is a Nash-equilibrium. From (A22), we have that $\phi^N \leq 1$ for $L \leq L_{1N}(\alpha), \alpha \leq \bar{\alpha}$, where

$$L_{1N}(\alpha) \equiv \frac{2\kappa}{\sqrt{2\alpha^6 + 4\alpha^4 + 3\alpha^2 + 1}}. \tag{A24}$$

Define $\alpha_{1N}(L)$ as the inverse function of $L_{1N}(\alpha)$. It is easy to verify that $\alpha_{1N}(L)$ is a decreasing function of α. Finally, let $\phi^N > 1$. From the definition of ϕ^N, it may easily be seen that $\partial \pi_C^{\phi}(\phi_i, \phi^N)/\partial \phi_i > 0$ for all $\phi_i \in [0, 1]$, for i, j = 1,2. Thus, the Nash-equilibrium of the financing stage is (1,1). Finally, by direct substitution of (A14) into (26) we obtain in equilibrium customer's profits are given by

$$\pi_C^{\phi,\phi} = \frac{\kappa q^2}{2} \frac{2(2-\phi^{N*})(1+\alpha^2\phi^{N*}) - 1}{[2\kappa + L(1+\alpha^2\phi^{N*})]^2}, \tag{A25}$$

concluding the proof. □

Proof Proposition 5. For the purpose of this proof, define $y \equiv L^2$ and $x \equiv \alpha^2$. Since $0 \leq L \leq 1$, and $\alpha \geq 0$, these are monotone transformations. From the definition of ϕ^N, and differentiating with respect to y, we have:

$$\frac{\partial \phi^N}{\partial y} = 4\kappa^2 \frac{8\kappa^2 - (4x^2y + 3xy + y) - \sqrt{\Delta}}{y^2(1+2x)\sqrt{\Delta}}, \tag{A26}$$

where $\Delta \equiv 64\kappa^4 + y[x^2y - 16\kappa^2(4x^2 + 3x + 1)]$. Since the denominator of (A26) is always positive, and the derivative is positive if and only if:

$$8\kappa^2 - (4x^2y + 3xy + y) > \sqrt{\Delta}. \tag{A27}$$

Note now that, from (A24), we have that x > 0 and $\phi^N < 1$ together imply that $y < 4\kappa^2/(2x^3 + 4x^2 + 3x + 1) < 8\kappa\kappa 2/(4x^2 + 3x + 1)$. Thus, the LHS of (A27) is positive, and (A26) is positive if and only if

$$[8\kappa^2 - (4x^2y + 3xy + y)]^2 > \Delta\,, \tag{A28}$$

which can be verified to be the case by direct calculation. Differentiating now with respect to x, we obtain that

$$\frac{\partial \phi^N}{\partial x} = \frac{(128x+32)\kappa^4 - 4y(16x^3+18x^2+11x+2)\kappa^2 + y^2x^3 - [4\kappa^2(4x+1) - y(3x^2+4x+1)]\sqrt{\Delta}}{y(1+2x)^2x^2\sqrt{\Delta}} \tag{A29}$$

Note that again $\phi^N < 1$ implies that $y < 4\kappa^2/(2x^2 + 4x^2 + 3x + 1) < 4\kappa^2(4x + 1)/(4x^2 + 3x + 1)$. Thus, the derivative in (A29) is positive if and only if

$$\sqrt{\Delta} \;<\; \frac{4y(16x^3+18x^2+11x+2)\kappa^2 - y^2x^3 - (128x+32)\kappa^4}{4\kappa^2(4x+1) - y(3x^2+4x+1)} \;\equiv\; B. \tag{A30}$$

From (A28), it easy to see that (A30) is verified if $8\kappa^2 - 3xy - y - 4yx^2 \le B$. By direct calculation, the latter inequality is verified if and only if $y \le 4\kappa^2/(3x^2 + 3x + 1)$, which is again implied by $\phi^N < 1$. □

Proof of Proposition 6. In the monopolistic case, the customer will solve:

$$\max_{\phi\, T}\ \pi_M^{\phi} = \epsilon(\phi^M)\frac{q}{2} + T - \frac{\kappa}{2}(E)^2$$
$$\text{s.t. } T + K = \epsilon(\phi^M)\frac{q}{2}(1-\phi_i), \tag{A31}$$

where $E = q/2\kappa$, and $\epsilon(\phi) = (1 + \alpha^2\phi)q/2\kappa$. Differentiating, we obtain that $\phi^{M*} = 0$, for $\alpha < \sqrt{2}/2$, and that $\phi^{M*} = \phi^M(\alpha) \equiv 1 - 1/2\alpha^2 < 1$ for $\alpha > \sqrt{2}/2$. Finally, from the definition of ϕ^N in (A22) it is easy to show that $\phi^N > \phi^M$ if and only if (A27) occurs, which we have shown to be the case. □

Proof of Proposition 7. To prove this proposition we need the following Lemma, which characterizes the Nash-equilibrium of the R&D race when one customer-research unit pair is integrated, while the other is not. Without loss of generality, we will denote again as pair1 the customer-research unit pair choosing integration, and as pair 2 the customer-research unit pair choosing non-integration. We maintain our assumption that κ is sufficiently large that $\epsilon_i < 1$, i.j = 1,2 and the Nash-equilibrium is stable.

Lemma A2. **If one customer-research unit pairs is integrated while the other is not integrated, the Nash-equilibrium of the R&D race is given by:**

$$e_1^{I,\phi^I} = 0, \qquad E_1^{I,\phi^I} = \epsilon_1^{I,\phi^I} = \frac{q[2\kappa - L(1+\alpha^2\phi^I)]}{2\kappa^2 - L^2(1+\alpha^2\phi^I)}, \tag{A32}$$

for the integrated pair (i.e. pair 1), and

$$e_2^{I_i,\phi^I} = \frac{\alpha q(\kappa - L)}{2\kappa^2 - L^2(1+\alpha^2\phi^I)}, \quad E_2^{I,\phi^I} = \frac{q\phi^I(\kappa - L)}{2\kappa^2 - L^2(1+\alpha^2\phi^I)}, \quad \epsilon_2^{I_i,\phi^I} = \frac{(1+\alpha^2\phi^I)q(\kappa - L)}{2\kappa^2 - L^2(1+\alpha^2\phi^I)}, \qquad \textbf{(A33)}$$

for the non integrated pair (i.e. pair 2).

Proof of Lemma2. Pair 1 is integrated, and will optimally set $\{e_1 = 0, E_1 = (q - L\epsilon_2)/\kappa\}$; thus $\epsilon_1 = (q - L\epsilon_2)/\kappa$. Pair 2, is non-integrated and will set $\{e_2 = \alpha\phi^I(q - L\epsilon_1)/2\kappa, E_2 = (q - L\epsilon_1)/2\kappa\}$; thus $_2 = (1 + \alpha^2\phi^I)(q - L\epsilon_2)/2\kappa$. Solving the Nash-equilibrium gives (A32) and (A33). □

The non-integrated pair, pair 2, must now determine the optimal retention ϕ^{I*} by solving problem (27), where the Nash-equilibrium of the effort subgame is given by (A32) and (A33). By direct calculation, the optimal retention ϕ^{I*} is now given by:

$$\begin{aligned} &\phi^{I*} = 0 && \text{for } 0 \le \alpha \# \alpha_{0I}(L), \\ &\phi^{I*} = \phi^I(\alpha, L) && \text{for } \alpha_{0I}(L) < \alpha \le \alpha_{1I}(L), \\ &\phi^{I*} = 1 && \text{for } \alpha \ge \alpha_{1I}(L), \end{aligned} \qquad \textbf{(A34)}$$

where

$$\phi^I(\alpha, L) \equiv \frac{L^2(1+\alpha^2) + 2\kappa^2(2\alpha^2 - 1)}{\alpha^2[4\kappa^2 - L^2(1+2\alpha^2)]}, \qquad \textbf{(A35)}$$

and $\alpha_{0I}(L)$, $\alpha_{1I}(L)$ are implicitly defined by setting $\phi^I(\alpha, L) = 0$ and $\phi^I(\alpha, L) = 1$, respectively. Customers' equilibrium profits in the integrated, pair 1, and non-integrated pair 2 are given by:

$$\pi_{C1}^{I,\phi} = \frac{q^2\kappa[2\kappa - L(1+\alpha^2\phi^{I*})]^2}{2[2\kappa^2 - L^2(1+\alpha^2\phi^{I*})]^2}. \qquad \textbf{(A36)}$$

$$\pi_{C2}^{I,\phi} = \frac{\kappa q^2(\kappa - L)^2[2(2-\phi^{I*})(1+\alpha^2\phi^{I*}) - 1]}{2[2\kappa^2 - L^2(1+\alpha^2\phi^{I*})]^2}, \qquad \textbf{(A37)}$$

Consider an (I,I) equilibrium. Integration is a symmetric Nash-equilibrium when $\pi_C^{I,I} = \kappa q^2/2(\kappa + L)^2 \ge \pi_{C2}^{I,\phi}$. Let $0 \le \alpha \le \alpha_{0I}(L)$, where $\phi^{I*} = 0$. By direct comparison, we have that $\pi_C^{I,I} \ge \pi_{C2}^{I,\phi}$ if and only if $0 < L < 1 < (2 + 2\sqrt{3})^{1/2}\kappa/2$. Consider now the case in which where $\alpha_{0I}(L) < \alpha \le \alpha_{1I}(L)$, where $\phi^{I*} = \phi^I(\alpha, L)$. In this case, by direct comparison, it may be verified that $\pi_C^{I,I} \ge \pi_{C2}^{I,\phi}$ if and only if $\alpha_{0I}(L) < \alpha < B_1(L)$, where

$$B_1(L) \equiv \sqrt{\frac{3\kappa^4 - L^4 + \sqrt{[\kappa^2(\kappa^2+2L^2)-2L^4][L^4-\kappa^2(2L^2-5\kappa^2)]}}{4\kappa^4+3L^4}} \quad \textbf{(A38)}$$

Finally, consider the case in which $\alpha > \alpha_{II}(L)$, where $\phi^{I*} = 1$. In this case, by direct comparison, it is easy to verify that $\pi_C^{I,I} \geq \pi_{C2}^{I,\phi}$ if and only if $\alpha_{II}(L) < \alpha < B_2(L)$, where

$$B_2(L) \equiv \sqrt{\frac{\kappa(\kappa^3 - \sqrt{\kappa^6 - 3L^4\kappa^2 + 2L^6})}{L^4}} \quad \textbf{(A39)}$$

Define then $\alpha_I(L) \equiv \min\{\bar{\alpha}; B_1(L)\}$ if $\alpha \leq \alpha_{II}(L)$, and $\alpha_I(L) \equiv \min\{\bar{\alpha}; B_2(L)\}$ if $\alpha > \alpha_{II}(L)$.

Consider now a (N,N) equilibrium. Non-integration is a symmetric Nash- equilibrium when $\pi_C^{\phi,\phi} \geq \pi_{C1}^{I,\phi}$, where $\pi_C^{\phi,\phi}$ is defined in (A25) and ϕ^{N*} is defined in (27). Let $0 \leq \alpha \leq \min\{\alpha_{0I}(L), \alpha_{0N}(L)\}$ so that $\phi^{I*} = \phi^{N*} = 0$. In this case, by direct calculation it is easy to verify that $\pi_C^{\phi,\phi} = 3/(2\kappa + L^2)^2 < (2\kappa - L)^2/(2\kappa^2 - L^2) = \pi_{C1}^{I,\phi}$. Thus, in this range, (N,N) is not a Nash-equilibrium. Consider now α such that $\max\{\alpha_{II}(L), \alpha_{1N}(L)\} \leq \alpha \leq \bar{\alpha}$. In this region, we have that $\phi^{I*} = \phi^{N*} = 1$. Direct calculation shows that $\pi_C^{\phi,\phi} \geq \pi_{C1}^{I,\phi}$, if and only if

$$L \geq L_{N1}(\alpha) \equiv \left[2\kappa^2 \frac{1-(1-\alpha^2)\sqrt{2\alpha^2+1}}{\alpha^4(\alpha^2+1)}\right]^{\frac{1}{2}}. \quad \textbf{(A40)}$$

It easy to show that the inequality in (A41) is always verified for $\alpha \geq (3/2)^{1/2}$. Consider now $\phi^I(\alpha, L, \kappa)$ and $\phi^N(\alpha, L, \kappa)$. It is easy to verify that $\phi^I(\alpha = (3/2)^{1/2}, L = 1, \kappa) > 1$ for $\kappa > 2.31$. Similarly, $\phi N(\alpha = (3/2)^{1/2}, L = 1, \kappa) > 1$ for $\kappa > 2.16$. This implies that $\pi_C^{\phi,\phi} > \pi_{C1}^{I,\phi}$ for $\kappa \geq \kappa_0 \equiv 2.31$. Let then $\alpha_S(L) \equiv \max\{\alpha_{0I}(L), \alpha_{0N}(L)\}$.

Define now $\Delta(\alpha, L, \kappa) \equiv \pi_C^{\phi,\phi}(\alpha, L, \kappa) - \pi_{C1}^{I,\phi}(\alpha, L, \kappa)$. We have already shown that for $\alpha \leq \min\{\alpha_{0I}(L), \alpha_{0N}(L)\}$ we have that $\Delta(\alpha, L, \kappa) < 0$. If $\max\{\alpha_{0I}(L), \alpha_{0N}(L)\} \leq \alpha \leq \bar{\alpha}$, we have just shown that in this region we have that $\pi_C^{\phi,\phi} > \pi_{C1}^{I,\phi}$ for $\kappa \geq \kappa_0$. Thus, there exists at least one $\alpha(L)$ such that $\Delta(\alpha, L, \kappa) = 0$. By direct numerical calculation it may be shown that for $\kappa \geq 2$, there is a unique value $\alpha(L) > 1$ such that $\Delta(\alpha, L, \kappa) = 0$. Define then $\alpha_\phi(L)$ such that $\Delta(\alpha_\phi(L), L, \kappa) = 0$. Let now $\min\{\alpha_{0I}(L), \alpha_{0N}(L)\} < \alpha < \max\{\alpha_{II}(L), \alpha\ 1N(L)\}$. If $\Delta(\bar{\alpha}, L, \kappa) > 0$, then, again, for $\kappa \geq 2$, by direct numerical calculation it may be shown that there exists at least one $\alpha(L)$ such that $\Delta(\alpha, L, \kappa) = 0$. In this case, define again $\alpha_\phi(L)$ such that $\Delta(\alpha_\phi(L), L, \kappa) = 0$. If instead, $\Delta(\bar{\alpha}, L, \kappa) < 0$, then define $\alpha_\phi(L) \equiv \bar{\alpha}$.

For $\alpha_I(L) < \alpha < \alpha_\phi(L)$ we have that $\pi_{C1}^{I,\phi} > \pi_C^{\phi,\phi}$ and $\pi_C^{I,I} < \pi_{C2}^{I,\phi}$. Thus, the strategy combination in which one customer chooses integration, while the other customer chooses non integrations is an asymmetric Nash-equilibrium.

Finally, by direct differentiation, it may be verified that $\partial \alpha_I(L)/\partial L > 0$, if $\kappa > 2.0402$. Direct inspection of (A24) also shows that $\partial \alpha_S(L)/\partial L < 0$. □

Proof of Proposition 8. For $\alpha < \sqrt{2}/2$, we have $\phi^{M*} = 0$. In this case, $\pi_M^I = q^2/2\kappa > 3q^2/8\kappa = \pi_M^N$ and integration is optimal. If $\alpha \geq \sqrt{2}/2$, we have $\phi^M(\alpha) \equiv 1 - 1/2\alpha^2$. In this case

$$\pi_M^I = \frac{q^2}{2\kappa} < \frac{q^2}{16}\frac{4\alpha + 2\alpha^2 + 1}{\kappa\alpha^2} = \pi_M^N \qquad \textbf{(A41)}$$

for if $\alpha \geq \sqrt{2}(1+\sqrt{5})/4$, and non-integration is optimal. □

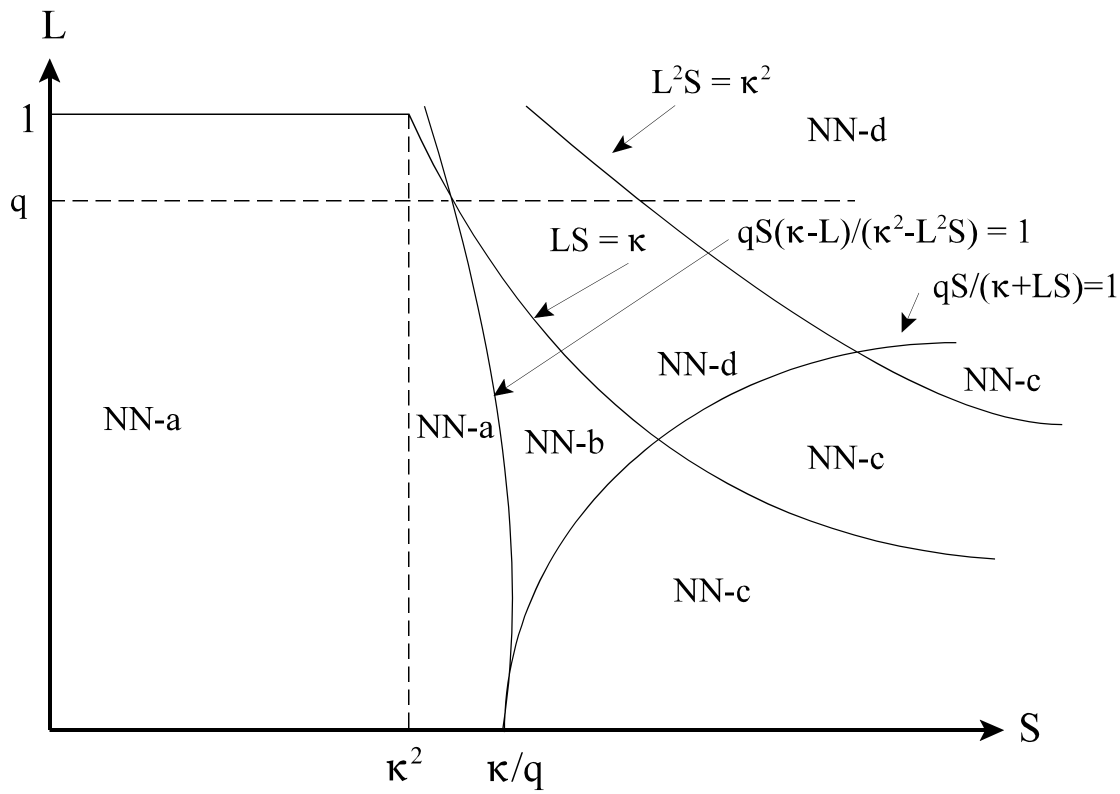

L
1
q
L²S = κ²
NN-d
LS = κ
qS(κ-L)/(κ²-L²S) = 1
qS/(κ+LS)=1
NN-d
NN-c
NN-a
NN-a
NN-b
NN-c
NN-c
S
κ²
κ/q

Figure A1

Table A1: Profits under Competition: The Integration and Non-Integration case (I-N)

if $qS(\kappa-L)/(\kappa^2-L^2S) < 1$	
$SL^2<\kappa^2$	$SL^2 \geq \kappa^2$
$\pi^{I,N}_{RU,1} = 0$ $\pi^{I,N}_{RU,2} = \frac{q^2(1+2S)(\kappa-L)^2}{2(2\kappa^2-2L^2S)^2}$	$\pi^{I,N}_{RU,1} = 0$ $\pi^{I,N}_{RU,2} = \frac{q\kappa-L(q-L)}{2\kappa} - \frac{\kappa(2S-1)}{8S^2}$
$\pi^{I,N}_{C,1} = \frac{q^2(2\kappa-2LS)^2}{2(2\kappa^2-2L^2S)^2}$ $\pi^{I,N}_{C,2} = \frac{q^2(4S-1)(\kappa-L)^2}{2(2\kappa^2-2L^2S)^2}$	$\pi^{I,N}_{C,1} = \frac{(q-L)^2}{2}$ $\pi^{I,N}_{C,2} = \frac{q\kappa-L(q-L)}{2\kappa} - \frac{\kappa}{8S^2}$
$\pi^{I,N}_{T,1} = \frac{q^2(2\kappa-2LS)^2}{2(2\kappa^2-2L^2S)^2}$ $\pi^{I,N}_{T,2} = \frac{3q^2S(\kappa-L)^2}{(2\kappa^2-2L^2S)^2}$	$\pi^{I,N}_{T,1} = \frac{(q-L)^2}{2}$ $\pi^{I,N}_{T,2} = \frac{q\kappa-L(q-L)}{2\kappa} - \frac{\kappa}{4S}$

if $qS(\kappa-L)/(\kappa^2-L^2S) \geq 1$	
$SL^2<\kappa^2$	$SL^2 \geq \kappa^2$
$\pi^{I,N}_{RU,1} = 0$ $\pi^{I,N}_{RU,2} = \frac{q\kappa-L(q-L)}{2\kappa} - \frac{\kappa(2S-1)}{8S^2}$	$\pi^{I,N}_{RU,1} = 0$ $\pi^{I,N}_{RU,2} = \frac{q\kappa-L(q-L)}{2\kappa} - \frac{\kappa(2S-1)}{8S^2}$
$\pi^{I,N}_{C,1} = \frac{(q-L)^2}{2}$ $\pi^{I,N}_{C,2} = \frac{q\kappa-L(q-L)}{2\kappa} - \frac{\kappa}{8S^2}$	$\pi^{I,N}_{C,1} = \frac{(q-L)^2}{2}$ $\pi^{I,N}_{C,2} = \frac{q\kappa-L(q-L)}{2\kappa} - \frac{\kappa}{8S^2}$
$\pi^{I,N}_{T,1} = \frac{(q-L)^2}{2}$ $\pi^{I,N}_{T,2} = \frac{q\kappa-L(q-L)}{2\kappa} - \frac{\kappa}{4S}$	$\pi^{I,N}_{T,1} = \frac{(q-L)^2}{2}$ $\pi^{I,N}_{T,2} = \frac{q\kappa-L(q-L)}{2\kappa} - \frac{\kappa}{4S}$

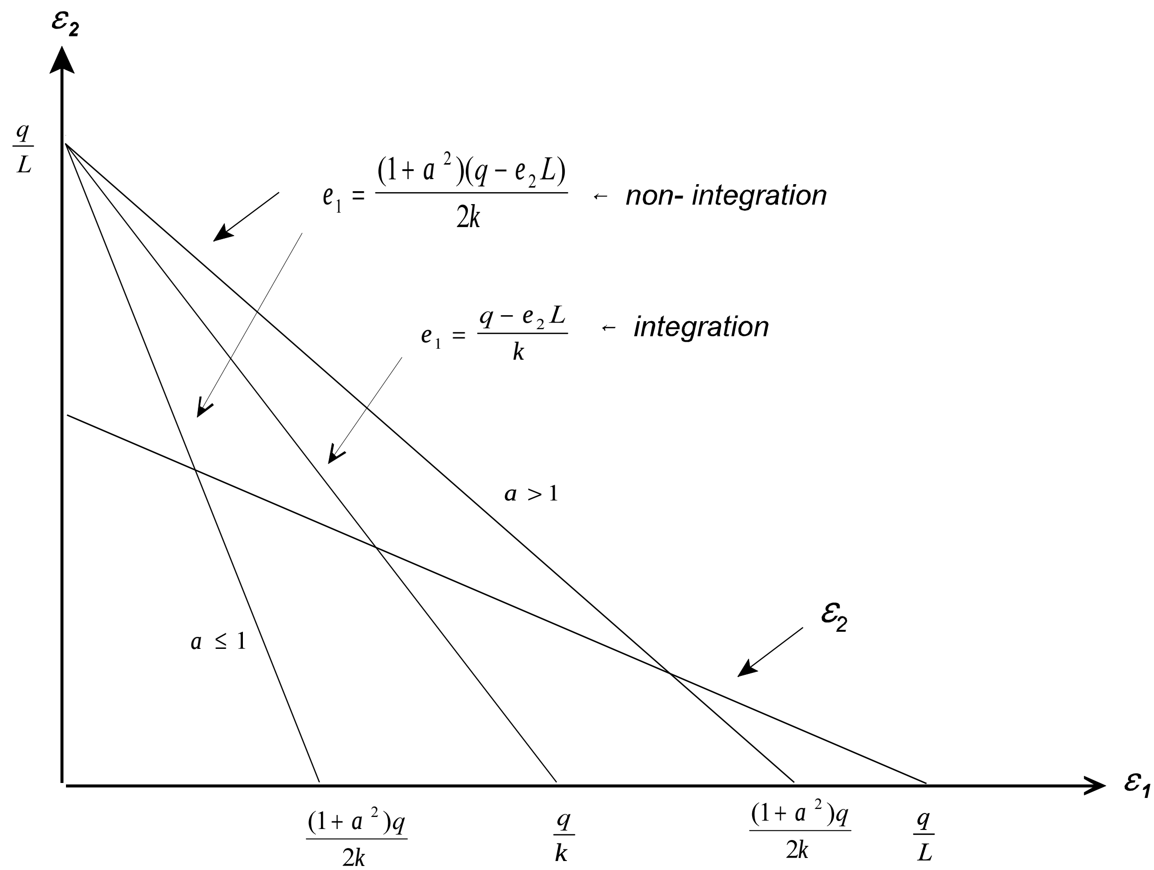


Figure 1: Organization structure and the Nash-Equilibrium of the R&D game.

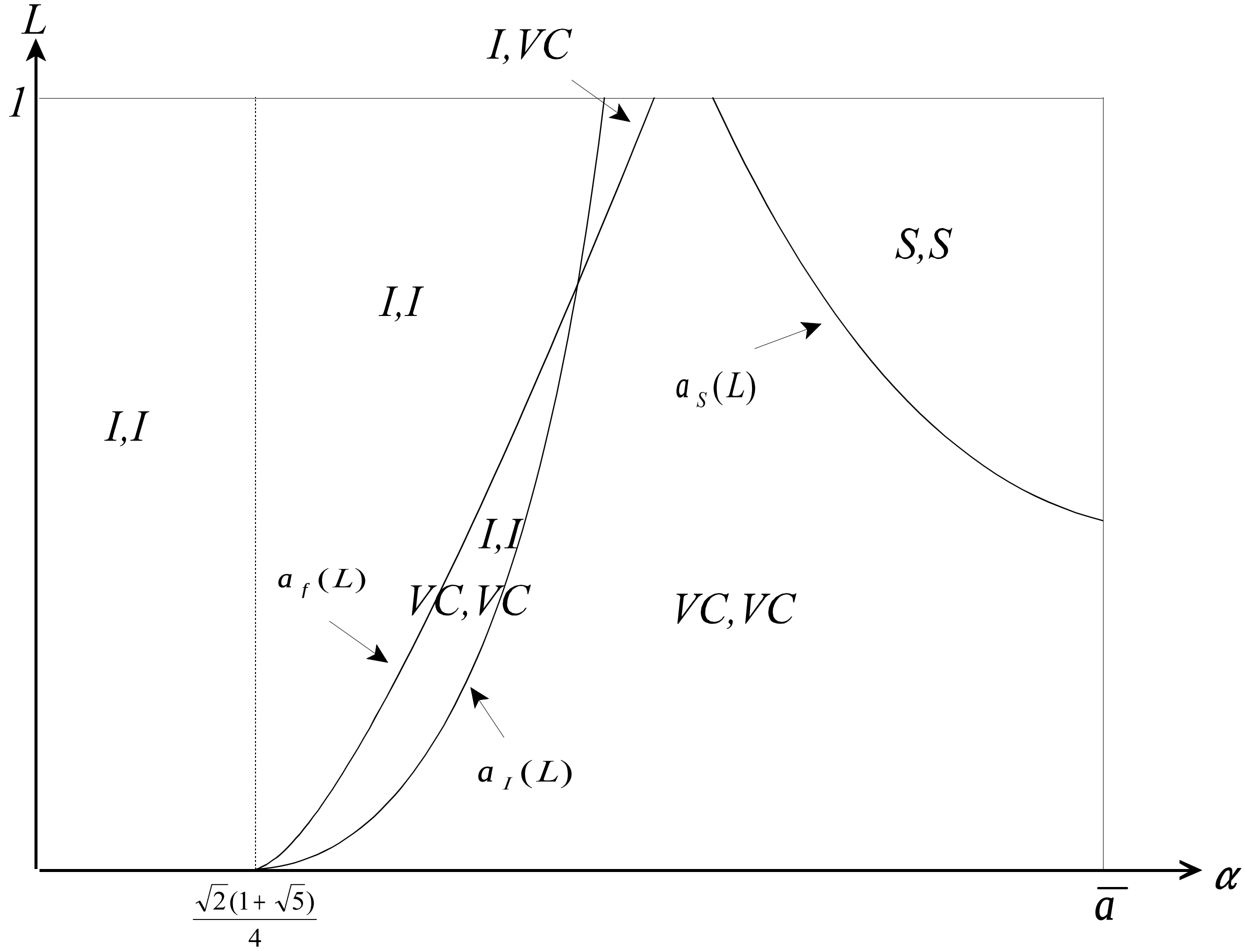


Figure 2: The ownership and financing of innovation.