Knowledge Spillovers, Competition, and Taste for Science in a Model of R&D Incentive Provision*

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February 26, 2010

Abstract

This paper develops a multi-task model to study the effects of product market competition and knowledge spillovers on the provision of incentives to scientific workers, as well as the effects of scientists' intrinsic motivations to perform research on the shape of the optimal incentive contract. We show that the degree of knowledge spillovers and of product market competition have an independent impact on the optimal incentive scheme, but, crucially, these effects also interact. First, high knowledge spillovers lead firms to soften incentives in order not to benefit competitors, but only when product market competition is high; in contrast, greater knowledge spillovers positively affect the provision of incentives when competition is low. Second, the relationship between the intensity of competition and the power of incentives is U-shaped, with the exact shape depending on the degree of knowledge appropriability. We also show that the performance-contingent pay for both applied and basic research increases with non-pecuniary benefits scientists obtain from performing research, while a trade-off may exist between non-monetary rewards and the fixed component of the wage. We discuss the implications of our findings for management as well as for empirical research.

*We are grateful to Kevin Boudreau, Erika Färnstrand Damsgaard, Rebecca Henderson, Ramana Nanda, Heather Royer, Mark Schankerman, Justin Sydnor, and seminar participants at Boston University, Georgia Tech, the EARIE 2007 Meeting, the EEA 2008 Meeting and the University of Bologna for their comments and suggestions. Tina Chen provided excellent research assistance.

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1 Introduction

The management of scientific workers and the design of effective incentives for them present numerous challenges for business organizations and are considered key determinants of competitive success.[1] A major challenge concerns the choice whether to provide high-powered incentives based on the scientists' performance, or to soften incentives instead and let the researchers' quest for reputation drive their effort. Another difficulty is how to measure performance in the first place, since research is a complex activity with no necessarily immediate returns. A further set of issues concerns how the characteristics of the markets where a company operates, and in particular the level of competition and the level of knowledge appropriability, affect the type and strength of incentives.

In this paper, we show that not only all of these challenges affect the determination of incentives to company scientists, but that these different dimensions interact in interesting ways.

In Section 2, we propose a model of incentive provision to company scientists where four key aspects emerge as important to study how scientific workers are motivated in the workplace. First, scientists engage in multiple, different activities (Cockburn et al. 2006). Second, the outcome of research activities, knowledge, is only imperfectly appropriable (Arrow 1962, Spence 1984). Third, while scientists are responsive to the provision of monetary incentives, they also care about less material outcomes, such as their reputation among peers (Dasgupta and David 1994, Merton 1973). Fourth, the provision of incentives to scientists, and to all workers in general, is likely to depend on the conditions a firm faces in the product market, such as the intensity of competition (Raith 2003, Schmidt 1997, and Vives 2008).

In the model, two firms compete in an industry by offering differentiated products, and designing incentives for their scientists (simplified to be a single agent per firm) to invest in cost-reducing research. Scientists engage in two types of non-contractible efforts. The first kind of effort – which we call applied research – does not provide non-pecuniary benefits to the scientists and does not generate knowledge spillovers to the rival firm; the second kind of effort – we call it basic research – provides non-pecuniary benefits to scientists but spills over to the rival firm. The owners offer a wage contract to the scientists contingent on observable signals. The signals can include, for example, patents and scientific articles.

The model produces two sets of results, discussed in Section 3, characterizing the optimal (linear) contract for the scientists. The first set of results highlight how the provision of incentives

[1] Andersson et al. (2009), Dennis (1987), Henderson and Cockburn (1994), Lamoreaux and Sokoloff (1999), Lerner and Wulf (2006), Sauermann and Cohen (2008), Zucker and Darby (1995).

for basic and applied research depends not only on the intensity of competition and the degree of knowledge spillovers, but also on the *interaction* between these two environmental conditions. High knowledge spillovers do not necessarily reduce the incentives to perform R&D: if competition is low, then firms provide high-powered incentives for both basic and applied research, since their dominant position in the product market reduces the negative effects of spillovers while allowing firms to enjoy each other's produced knowledge. With high competition, not only do we derive that incentives for basic research effort, which produces spillovers, decrease as spillovers become more pervasive, we also show that it is optimal to mute incentives for applied research effort, even if it does not generate spillovers. In turn, the impact of product market competition on the strength and direction of R&D incentives depends on the degree of knowledge spillovers. If knowledge spillovers are low, firms provide the strongest incentives for basic and applied research both when they face very little competition (since cost reduction through R&D has a bigger absolute impact on profits), and when competition is very high (for competitive pressure makes any small cost reduction a proportionally large one, as profits are lower). Thus, the relationship between the intensity of competition and the power of incentives to scientists is U-shaped. In contrast, when there are high levels of spillovers, the strength of incentives is decreasing in the intensity of competition. A further implication of these findings is that incentives for basic and applied research are complementary only if either the level of product market competition or the degree of spillovers is low.

The second set of results concern the impact of a scientist's non-monetary motivation to perform basic research, or taste for science, on her pay scheme. The response of scientists to steeper incentives is stronger when they also have high intrinsic motives to perform basic research. As a consequence, companies optimally provide stronger incentives to intrinsically motivated scientists, both for basic research and applied research, even if the latter does not generate non-monetary benefits to the scientists. Thus, the incentives for basic and applied research and the degree of taste for science are complementary. We show, in contrast, that a trade-off between monetary pay and non-monetary rewards can occur at the level of the fixed salary. Empirically, one would therefore need to distinguish between fixed and contingent components of a scientist's wage in order to properly study the relation between monetary pay and intrinsic motivations.

In Section 3 we also discuss how our analysis contributes to throwing a new light on a number of empirical results in the literature on the provision of incentives to company scientists. Cockburn et al. (2006), for example, find that, in the pharmaceutical industry, the incentive instruments to stimulate different types of research (basic and applied) are complementary. We show that this result might depend crucially on the level of product market competition. Andersson et al.

(2009) find that wages are more responsive to performance in more "risky" industry segments. The authors claim that this result can be explained with the fact that star developers are more likely to be hired in risky segments of the industry. We add that, if riskier segments of the industry are more concentrated (as some evidence seems to show), and since intellectual property protection in software is weak, then our model predicts that companies offer higher powered incentives in less competitive product lines. Software workers, moreover, may also derive non-monetary benefits from their work (Lakhani and von Hippel 2003). If developers with higher non-monetary motivations prefer to work in more risky lines (because success may bring greater "fame" among peers, for example), then our model predicts that these workers will have steeper performance pay schemes. Under the assumption that company scientists also have non-monetary motivations for their work, Stern (2004) finds that firms that allow their researchers to publish their findings, or even reward scientists for their publications, offer lower monetary wages. Our model qualifies this result in that we predict that the fixed component of the wage might be negatively related to the taste for science, but the contingent component increases for scientists who have higher non-monetary motivations.

The model in this paper shares some similarities with previous theoretical works. Schmidt (1997), Raith (2003) and Vives (2008), among others, analyze the provision of incentives to managers as they are affected by competition in the product market. Spence (1984), Qiu (1997), and Zhang and Zhang (1997) consider the presence of knowledge spillovers in R&D investments. We contribute to these studies by showing that the impact of each of these two environmental factors crucially depend on the other. Murdock (2002) considers a model where agents also have intrinsic motivations for the completion of projects, but the principal may prefer not to implement some of these projects if they have negative expected financial returns. Implicit contracts where the principal commits to implement the projects preferred by the agent may be socially superior and are more likely to be chosen by a principal when the agent's intrinsic motivation is higher (see also Manso 2007). Murdock's model, therefore, studies the relationship between decision right allocation and the intrinsic motivation of agents, while our model analyzes the shape of the optimal incentive contracts as it responds to non-monetary motives of agents. Besley and Ghatak (2005) develop a model of matching with intrinsically motivated agents and show that monetary and non-monetary incentives are substitutes. In their model, the reward of the principal is unaffected by the agent's intrinsic motivation, thus the principal exploits intrinsic motivation to save on the cost of high-powered incentives. In our model, the taste for science, through its impact on the desire to perform basic research, directly impacts the principal's payoff, thus leading to complementarity. Finally, Banal-Estañol and Macho-Stadler (2010) study the time allocation problem among different activities of a researcher who responds to both financial and scientific incentives, and show that higher financial incentives can lead a scientist to opt for riskier projects. Their study, however, abstracts from the analysis of the impact of knowledge appropriability and product market competition.

Section 4 explores the managerial implications of our findings. In highlighting the interaction between the conditions in the product market and the ease of transmission of knowledge, our results inform R&D managers on the importance to look at their company's position in the product market and at the knowledge appropriability conditions for different types of activities when designing their internal incentive schemes. R&D managers, moreover, need to consider the different degrees of interest for monetary pay and for their reputations of their scientists. Scientists who are more eager to maintain their links to the scientific community even when employed by a firm, and are allowed to do so, are not necessarily "cheap." Instead, these are the scientists who are given more powerful incentives for the performance of both basic and applied research.

Section 5, finally, offers concluding remarks. Appendix A summarizes the notation of the model and reports the figures, while all proofs are gathered in Appendix B.

2 The Model

2.1 Setup

The model is built as a four-stage game whose timing is represented in Figure 1 and whose detailed description follows.

[Figure 1 about here]

Two risk-neutral firms, i and j, compete on the product market à la Cournot. The inverse demand function for firm i is given by:

$$p_i = A - q_i - \lambda q_j, \tag{1}$$

where p_i is the price, q_i is the quantity, and $\lambda \in [0, 1]$ is a parameter indicating the intensity of competition with the rival firm j. The limit case of $\lambda = 0$ reflects the firms being monopolists in separate markets. The opposite limit case of $\lambda = 1$ represents the standard case of Cournot competition with homogeneous products.[2] The total cost function for firm i is:

$$TC_i = c_i q_i. \tag{2}$$

[2] As shown by Singh and Vives (1984), the inverse demand function in (1) can be obtained by the maximization problem of a representative consumer with utility function: $U(q_1, q_2) = A(q_1 + q_2) - \frac{(q_i^2 + 2\lambda q_i q_j + q_j^2)}{2}$.

The marginal cost c_i is a function of the (unobservable, unverifiable) effort that a scientist, hired by the company's principal, exerts before competition in the product market occurs. Effort has two dimensions: applied (e_i^A) and basic (e_i^B) research. The marginal cost, in turn, is non-contractible. The relation between marginal production costs and scientific effort is:

$$c_i = c - e_i^A - e_i^B - \beta e_j^B, \tag{3}$$

where c is a constant and $\beta \in [0, 1]$. Scientific efforts reduce marginal costs, e.g., by facilitating process innovations. In addition, the effort in basic research of firm j's scientist reduces the marginal costs of firm i because basic research is not perfectly appropriable. The size of the parameter β determines the degree of knowledge spillovers.

Notice that the intensity of knowledge spillovers between companies need not be related to the intensity of product market competition. Even when product markets are separated, for instance, the relevant knowledge that allows innovation for one product can be relevant for the other product. Furthermore, while different geographical areas may be isolated in terms of final product competition (e.g. by regulation), researchers can still communicate and diffuse their knowledge through other channels. Conversely, firms may operate in similar markets and compete fiercely, but use different technologies, so that knowledge spillovers are low.[3]

The scientists derive utility both from monetary rewards, and from the possibility to engage in basic research activities. In addition to caring about money, scientists therefore have a "taste for science."[4] Effort costs are quadratic and separable. The utility function of a scientist hired by firm i is:

$$U_i = -\exp\left\{-r\left[w_i + \rho e_i^B - \gamma\left(\frac{\left(e_i^A\right)^2}{2} + \frac{\left(e_i^B\right)^2}{2}\right)\right]\right\}, \tag{4}$$

[3] As an example of research aimed at a given market segment that ends up being relevant for different segments, consider the research for cardiovascular-related diseases that turned out to be useful for the correction of erectile dysfunctions (Kling 1998, Pietsch 2006). Similarly, airplane producers and automakers, or computer and cellphone manufacturers, use similar technologies but do not operate in the same markets (Bloom et al. 2008). Alcacer and Zhao (2007) and Bloom et al. (2008), moreover, document that firms that compete with each other may employ different technologies.

[4] The fact that the scientists' utility depends both on monetary returns and on a taste for science is similar to assuming that scientists have both extrinsic and intrinsic motivations. A recurrent theme in the literature on intrinsic and extrinsic motivation is related to the "crowding out" effect, i.e. the idea that extrinsic motivation (in our case, high-powered incentives) would undermine intrinsic motivation (in our case, the taste for science). We rule out this possibility, by assuming that the monetary and non-monetary component of the utility function are independent. Bénabou and Tirole (2003) develop a model where "crowding out" effects are likely to occur when a principal has private information about the task or the agent's characteristics, and the agent infers such information from the principal's behavior. These conditions do not seem to fit our case.

where $r \geq 0$ is the coefficient of absolute risk aversion, $\rho > 0$ is the degree of taste for science and $\gamma > 0$ is a parameter inversely related to the productivity of applied and basic research. The scientist's reservation utility is denoted with $\overline{u}$.

In (4), a value of r strictly greater than zero indicates that the scientist is risk averse, while the extreme case of $r = 0$ indicates risk neutrality. Below we solve the model for the risk neutrality case. Our key results are qualitatively the same under risk aversion, though the analysis is algebraically more cumbersome. A full version of the model with risk aversion is available from the authors.[5]

The non-contractibility of marginal costs and profits does not allow the scientist's wage to be contingent, say, on profits. The firm proposes an incentive contract on other verifiable measures. The verifiable signals, X^A and X^B, are functions, respectively, of e^A and e^B, and of stochastic shocks. Think of these signals as some observable measures of a scientist's effort in applied research (e.g. the number or the value of the obtained patents) and in basic research (e.g. the number or relevance of the publications a scientist has. See for example Cockburn et al. 2006, Henderson and Cockburn 1994).[6] Define:

$$X_i^A = e_i^A + \varepsilon_i^A; \tag{5}$$

$$X_i^B = e_i^B + \varepsilon_i^B, \tag{6}$$

where ε_i^A and ε_i^B represent random shocks with zero mean. The wage schedule firm i proposes to scientist i takes a linear form:

$$w_i = \alpha_i^0 + \alpha_i^A X^A + \alpha_i^B X^B, \tag{7}$$

where the variables α_i^0, α_i^A and α_i^B are under the control of the firm. The setup for firm j is fully symmetrical to that for firm i as just described.

The wage contract is offered simultaneously by the two firms to their own scientist, before effort is provided, and the scientist is paid at the realization of the performance measures, which can be

[5] In fact, the agent's risk attitude is not at the core of our analysis. While risk aversion has been traditionally a basic element of principal-agent models, Gibbons (2005) suggests examples of recent contributions in agency theory where other aspects (such as multi-task) provide key insights even with risk neutrality. Similarly, assuming different values of the cost parameter γ for applied and basic research makes the expressions more complex, but it does not provide any further insight. In fact, even for identical γ, the effective costs of applied and basic research differ due to the presence of ρ. Results with different cost parameters, e.g. γ^A and γ^B, are also available upon request.

[6] The non-contractibility of costs and profits can be considered as a natural assumption in the context of small, entrepreneurial firms, where monitoring costs are high and most financial information is not public. In addition, we model costs as deterministic function of efforts. An alternative formulation would be to model costs as *random* functions of efforts, while assuming they are contractible, as in Raith (2003). In this case, we could consider also contracts contingent on profits as in Hart (1983). Or, one could include in the model the choice of which observables to base the contract on, as in Piccolo et al. (2008). However, if signals for efforts are available, contracts contingent on such signals only would be optimal if c was a random variable itself, and agents were sufficiently risk averse.

assumed to occur before the firms compete on the market.

2.1.1 An analysis of the model's assumptions

Before we solve the model, a few observations on its robustness to different specifications are in order. First, we consider only the case of Cournot competition. Other forms of competition, notably Bertrand, could be used, raising the question whether these other forms would lead to different results. In the case of one-dimensional effort, Cournot competition is more conducive to cost-reducing R&D than Bertrand competition, ceteris paribus, because of the "strategic effect" (Qiu, 1997). With Cournot competition, higher investments in R&D make the firm tougher in the market and this discourages its rival's sales. In the case of price competition, the firm's R&D lowers costs and induces a rival to cut its price, which is detrimental to both. As a consequence, the type of competition does affect the level of the piece rates. In addition, some specific results below depend on the type of competition being Cournot. For instance, the (possible) U-shaped relation between strength of incentives and intensity of competition relies on Cournot competition, for Schmutzler (2010) shows that the relation between substitutability and R&D investment is unambiguously negative under Bertrand competition (for one-dimensional effort). Other results, however, such as the co-movement of the piece rates for basic and applied research and the effects of changes in the taste for science, do not depend on the type of competition.[7]

Second, in the model, applied and basic research efforts enter linearly and separately into the cost function. An alternative specification could include an interaction term between the two efforts, capturing complementarities between applied and basic research. Notice, however, that the current formulation already induces complementarity between the two types of research, since an increase in the level of one type of research increases the marginal return from performing the other type. The intuition for this is as follows. Consider an exogenous increase in one of two efforts. This brings about a reduction in costs, which leads a firm to expand its size; in turn, the incentive to invest in the other type of effort increases since larger firms have stronger incentives in investing in cost-reducing innovation. If an interaction term is included in the cost function, this would add an additional source of complementarity between applied and basic research (of a purely knowledge nature in this case, rather than a strategic one) and would simply expand the area of the parameter space in which variations in the parameters lead to the same direction of change in the piece rates.[8]

[7] The co-movement of piece rates for applied and basic research depends on the cross-derivative of profits with respect to applied and basic research being positive, which would also hold under Bertrand competition, and on the degree of spillovers of basic research being higher than the one for applied research.

[8] A formal analysis of the effect of knowledge complementarities between applied and basic research is available upon request.

Third, while we consider only process innovations, the model can accommodate some types of product innovation in a natural fashion (Vives, 2008). In particular, quality improvements in existing products can be modeled as an increase in consumers' willingness to pay for a product. Suppose that the scientists' effort, instead of reducing the baseline marginal cost c, increases the maximum willingness to pay A in the demand function (1). As a consequence, the firms' profit functions, and therefore their optimal contract decisions, will be unaffected as compared to the case developed here.[9]

Fourth, notice that knowledge spillovers, in the model, do not occur directly through publications or patents. It is implicitly assumed that the firms can effectively protect their proprietary knowledge, even when it is made public through either patents or publications. The assumption is quite obvious as long as patents are concerned, but it is also a plausible choice with respect to publications: firms typically delay publications of their scientists (and of independent scientific partners) until confidential information and intellectual property are properly protected (Blumenthal et al. 1986, Lacetera 2006). Knowledge spillovers, however, can still occur through more informal and less verifiable channels. These channels include interpersonal relations and conversations among scientists from different organizations, as well as labor mobility. Plausibly, it is harder for a firm to control these flows of information. The model captures the difference between "appropriable" and "pure" knowledge spillovers by having the wage schedule depend on codified measures, e.g. publications (see expression (7) above), while knowledge spillovers occur directly through the unverifiable (by a third party) effort (as in the cost function (3)). The model also considers the fact that knowledge is more likely to be transmitted if it is more basic, as it is less firm-specific than knowledge from applied research, and that the transmission of knowledge is imperfect. The former fact is captured by having knowledge spillovers occur only through effort in basic research; the imperfection in the transmission of knowledge is captured by having β, i.e. the share of a scientist's basic research effort that benefits a rival firm, within the unit interval.

2.2 Deriving the optimal incentive scheme

The game is solved by backward induction, starting from the quantity choices in the product market. The focus is on firm i. The results for firm j are easily obtained.

[9] In contrast, our model cannot accommodate for innovations consisting in both the introduction of new products and changes in the degree of horizontal differentiation (and then, the intensity of competition.)

2.2.1 Market competition

Firm i solves

$$\underset{q_i}{Max}\Pi_i = (p_i - c_i)q_i = (A - q_i - \lambda q_j - c_i)q_i. \tag{8}$$

Solving for the (necessary and sufficient) first order condition for q_i gives the equilibrium quantity and profits:

$$q_i^* = \frac{A - \frac{(2c_i - \lambda c_j)}{2-\lambda}}{\lambda + 2}; \tag{9}$$

$$\Pi_i^* = [q_i^*]^2 = \left[\frac{A - \frac{(2c_i - \lambda c_j)}{2-\lambda}}{\lambda + 2}\right]^2. \tag{10}$$

2.2.2 The scientist's effort choice

The effort choices of scientist i are straightforward to obtain, given the incentive scheme and the taste for science. They are increasing linearly in the piece rates and, as far as effort in basic science is concerned, in the degree of taste for science, and are decreasing in the difficulty of the tasks as represented by the cost parameter γ:

$$e_i^A = \frac{\alpha_i^A}{\gamma}; \tag{11}$$

$$e_i^B = \frac{\rho + \alpha_i^B}{\gamma}. \tag{12}$$

2.2.3 The principal's incentive provision problem

Following Holmstrom and Milgrom (1987), the principal's choice of the optimal contract is obtained from maximizing the expected total surplus TS, subject to the incentive compatibility constraints, given by the scientist's optimal effort choices. As discussed above, we solve the model under the assumption of risk neutrality of the scientist, i.e. $r = 0$. Then, the program can be written as:

$$\underset{\alpha_i^0, \alpha_i^A, \alpha_i^B}{Max} E(TS_i) = \Pi_i + \rho e_i^B - \gamma \left[\frac{\left(e_i^A\right)^2}{2} + \frac{\left(e_i^B\right)^2}{2}\right] \tag{13}$$

$$s.t. \text{ (11) and (12).}$$

Substituting the constraints (11) and (12) and the profits Π_i as expressed in (10) – where in turn we plug in the marginal cost function (3) – we obtain:

$$E(TS_i) = \left[\frac{A}{\lambda+2} - \frac{2(c - \frac{\alpha_i^A}{\gamma} - \frac{(\rho+\alpha_i^B)}{\gamma} - \beta(\frac{\rho+\alpha_j^B}{\gamma})) - \lambda(c - \frac{\alpha_j^A}{\gamma} - \frac{(\rho+\alpha_j^B)}{\gamma} - \beta\frac{(\rho+\alpha_i^B)}{\gamma})}{(2-\lambda)(\lambda+2)}\right]^2 \quad (14)$$

$$+\rho\,\frac{(\rho+\alpha_i^B)}{\gamma} - \; - \frac{(\alpha_i^A)^2}{2\gamma} - \frac{(\rho+\alpha_i^B)^2}{2\gamma}.$$

Invoking symmetry (i.e. $\alpha_i^A = \alpha_j^A$ and $\alpha_i^B = \alpha_j^B$) the first-order conditions become:[10]

$$\frac{\partial E(TS)}{\partial \alpha_i^A} = \left[A - c + \frac{\alpha_i^A}{\gamma} + \frac{(1+\beta)(\alpha_i^B+\rho)}{\gamma}\right]\left[\frac{4}{\gamma(2-\lambda)(2+\lambda)^2}\right] - \frac{\alpha_i^A}{\gamma} = 0; \quad (15)$$

$$\frac{\partial E(TS)}{\partial \alpha_i^B} = \left[A - c + \frac{\alpha_i^A}{\gamma} + \frac{(1+\beta)(\alpha_i^B+\rho)}{\gamma}\right]\left[\frac{2(2-\beta\lambda)}{\gamma(2-\lambda)(2+\lambda)^2}\right] - \frac{\alpha_i^B}{\gamma} = 0. \quad (16)$$

We assume that the second order conditions are satisfied.[11] Solving the system of first order conditions and defining $k \equiv (\lambda+2)^2(2-\lambda)$, we obtain:[12]

$$\alpha_E^A = \frac{16\left[\gamma(A-c)+\rho(1+\beta)\right]}{\gamma k - 4 - 2(1+\beta)(2-\beta\lambda)}; \quad (17)$$

$$\alpha_E^B = \frac{8\left[\gamma(A-c)+\rho(1+\beta)\right](2-\beta\lambda)}{\gamma k - 4 - 2(1+\beta)(2-\beta\lambda)}. \quad (18)$$

The subscript E stands for "Equilibrium." A series of comparative statics experiments on (17) and (18) are performed in the following Section.

3 Implications: the impact of competition, knowledge spillovers, and non-monetary motives on the optimal incentive contract

The model generates results regarding the strength, direction, and relation among the incentive instruments that a firm has under control in order to motivate scientists. The analysis of these results is divided into two parts. In the first part, we study how knowledge spillovers and the intensity of competition affect the relative and absolute strength of incentives, and determine the competitive and knowledge-appropriability conditions under which the two incentive rates are

[10] In equilibrium, α^0 will be chosen for the scientist's participation constraint to bind.

[11] This requires: $\frac{\partial^2 E(TS)}{\partial^2 \alpha_i^A} = \frac{8}{(\gamma)^2(2-\lambda)^2(2+\lambda)^2} - \frac{1}{\gamma} < 0$; $\frac{\partial^2 E(TS)}{\partial^2 \alpha_i^B} = \frac{2(2-\beta\lambda)^2}{(\gamma)^2(2-\lambda)^2(2+\lambda)^2} - \frac{1}{\gamma} < 0$; and $\frac{\partial^2 E(TS)}{\partial^2 \alpha_i^A}\frac{\partial^2 E(TS)}{\partial^2 \alpha_i^B} - \left(\frac{\partial^2 E(TS)}{\partial \alpha_i^A \alpha_i^B}\right)^2 = \left[\frac{8}{\gamma^2(2-\lambda)^2(2+\lambda)^2} - \frac{1}{\gamma^A}\right]\left[\frac{2(2-\beta\lambda)^2}{\gamma^2(2-\lambda)^2(2+\lambda)^2} - \frac{1}{\gamma^B}\right] - \left[\frac{4(2-\beta\lambda)}{\gamma^2(2-\lambda)^2(2+\lambda)^2}\right]^2 > 0.$

[12] We shall assume that $\gamma{>}1$ to guarantee that (17) and (18) are always positive. Furthemore, in order to simplify the proof of one proposition below, we shall assume $A - c \geq \rho$.

complementary. In the second part, we focus on how the presence of non-monetary motives that drive scientists to perform basic research affect the definition of the incentive contract. The results are presented as a series of propositions. The propositions are preceded by an informal description of, and the intuitions behind the results. Each of the two subsections concludes with a discussion of how the model helps to interpret the existing empirical evidence on the provision of incentives to corporate scientists.

3.1 Competition, Spillovers, and Incentives

3.1.1 The relative strength of incentives

The higher the competitive pressure on the product market and the higher the ease with which knowledge spills over to competitors, the stronger the incentives to perform applied research in comparison to basic research. Since spillovers occur only through basic research, firms find it relatively more profitable to reward those activities that, while reducing costs, do not produce externalities (thus benefiting competitors). When $\beta = 0$ or $\lambda = 0$, note that neither the intensity of competition nor the ease with which knowledge spills over to competitors has an effect on the relative strength of incentives.

Proposition 3.1 *The ratio between the two piece rates, $\frac{\alpha^A}{\alpha^B}$, is increasing in λ and β.*

3.1.2 Knowledge spillovers and the shape of the optimal contract

In general, the effect of knowledge spillovers from basic research (as measured by the parameter β) on the absolute strength of incentives is ambiguous. On the one hand, there is a positive effect of incoming spillovers. As previously noticed, larger firms have higher incentives to invest in cost-reducing R&D. Consequently, a decrease in unit costs due to larger incoming spillovers leads firms to provide stronger incentives both for basic and applied research. On the other hand, giving strong incentives to scientists benefits the competing firm by reducing its costs through outgoing spillovers, thus increasing the competitor's size and profits at the detriment of the firm originating the spillovers. This has a negative effect on the provision of incentives for basic research as well as for applied research, due to the firm's smaller size. The overall impact of the degree of knowledge spillovers turns out to depend crucially on the intensity of product market competition.

When the intensity of competition λ is sufficiently low, the positive effect of outgoing spillovers prevails, both α_E^A and α_E^B are increasing in β, and the negative impact of knowledge spillovers vanishes. Each firm is reinforced by the spillovers deriving from the other firm; this reinforcement, however, does not hamper the profitability of the originating firms since there is no direct interaction in the final market. As a consequence, firms exploit the cost-reducing impact of knowledge spillovers in full, by reinforcing the incentives to their scientists. At the other extreme, when both β and λ are high, $\frac{\partial \alpha_E^A}{\partial \beta}$ and $\frac{\partial \alpha_E^B}{\partial \beta}$ are both negative. Low investments in basic research lead firms to operate at higher costs, which is detrimental to the incentives for cost-reduction through applied research efforts. Finally, in the intermediate case, there is a "substitution effect" that favors applied research against basic research following from Proposition 3.1 above: firms provide higher incentives for applied research, which does not generate spillovers to competitors, while reducing the incentives for basic research for which spillovers to competitors are present. This leads to $\frac{\partial \alpha_E^A}{\partial \beta} > 0$ and $\frac{\partial \alpha_E^B}{\partial \beta} < 0$. The previous considerations are formalized in the following propositions and corollaries:

Proposition 3.2 *α_E^A is increasing in β if $\lambda < \lambda_A^*$, where λ_A^* is the unique solution to $\frac{\partial \alpha_E^A}{\partial \beta} = 0$, and λ_A^* is decreasing in β.*

Corollary 3.2.1 *α_E^A is always increasing in β if $\lambda < \frac{2}{3}$ or $\beta < \frac{1}{2}$.*

Proposition 3.3 *α_E^B is increasing in β if $\lambda < \lambda_B^*$, where λ_B^* is the unique solution to $\frac{\partial \alpha_E^B}{\partial \beta} = 0$, and λ_B^* is decreasing in β. Furthermore, $\lambda_B^* \leq \lambda_A^*$.*

Corollary 3.3.1 *α_E^B is always decreasing in β if $\lambda > \frac{2}{3}$ or $\beta > \frac{1}{2}$.*

Figure 2 provides a graphical example of these results, by showing the relevant regions for $\frac{\partial \alpha_E^A}{\partial \beta}$ and $\frac{\partial \alpha_E^B}{\partial \beta}$ in the (λ, β) space, while the other parameters are chosen in order to guarantee that the second order conditions are satisfied for all values of β and λ.

[Figure 2 about here]

3.1.3 Competition and the shape of the optimal contract

We now investigate the relationship between the strength of incentives provided to scientists and the intensity of competition as measured by λ. This analysis evokes the issue of the relationship between the intensity of competition and the incentives to innovate, which has been long debated in economics since Schumpeter (1943) and Arrow (1962). Again, the interaction between degree of knowledge spillovers and competition comes to play a key role.

There are two effects relating λ and the incentives to research. If λ is small, so that competition is limited, firms are larger, ceteris paribus. This provides high incentives for cost-reduction (such an effect can be seen in the denominator of (9), page 10). If λ is large, a firm's profits are more sensitive to its own costs and the other firm's cost (as can be seen from expression (9) representing the optimal quantities produced). This tends to reduce the incentives to innovation, especially when knowledge spillovers are high, since the marginal reduction of the other firm's cost is higher in this case.

The net effect of these contrasting forces is as follows. The coefficients α_E^A and α_E^B are decreasing in λ if $\lambda < \frac{2}{3}$, irrespective of β. If $\lambda > \frac{2}{3}$, there are three different regions. If β is sufficiently low, then both α_E^A and α_E^B are increasing in λ. This means that in this case the relationship between the intensity of competition and the power of incentives to the scientists is U-shaped, i.e. α_E^A and α_E^B are minimal for an intermediate level of λ.[13] For intermediate values of β, an increase in λ has a positive effect on α_E^A, but a negative effect on α_E^B. Again, a substitution effect is present since higher λ particularly reinforces the negative effect of spillovers on α_E^B when β is high. Finally, for high values of β, α_E^A and α_E^B are both decreasing in λ. In this case, lower investment in basic research also leads to a reduction in applied research.

Proposition 3.4 α_E^A *is increasing in* λ *if* $\lambda > \lambda_A^{**}$*,where* λ_A^{**} *is the unique solution to* $\frac{\partial \alpha_E^A}{\partial \lambda} = 0$*, and is increasing in* β*. If the critical value* λ_A^{**} *is greater than 1, then* α_E^A *is always decreasing in* λ*.*

Proposition 3.5 α_E^B *is always increasing in* λ *if* $\lambda > \lambda_B^{**}$*,where* λ_B^{**} *is the unique solution to* $\frac{\partial \alpha_E^B}{\partial \lambda} = 0$*, and is increasing in* β*. Furthermore,* $\lambda_B^{**} \leq \lambda_A^{**}$*.*

Figure 3 shows the relevant regions for $\frac{\partial \alpha_E^A}{\partial \lambda}$ and $\frac{\partial \alpha_E^B}{\partial \beta}$ in the (λ, β) space, using the same numerical values as in Figure 2 above.

[Figure 3 about here]

3.1.4 Are the incentive instruments complementary?

Ultimately, R&D managers are interested in the design of a whole incentive system for scientists, and not only in the choice of each single effort-enhancing measure (Cockburn et al. 2006, Holmstrom and Milgrom 1994). Our model also holds predictions on how the piece rates co-move, and in particular on their complementarity. The variables α_i^A and α_i^B are said to be complementary to a given parameter when an increase in the parameter leads to an increase in the marginal return from α_i^A and α_i^B, and, simultaneously, the increase in the level of one of the piece rates increases the marginal return from the other (Holmstrom and Milgrom 1994). Some of the complementarity

[13] This result extends Sacco and Schmutzler (2008), who consider unidimensional effort, and Belleflamme and Vergari (2006), where only one firm has access to innovation. Both models assume that innovations are always perfectly appropriable and do not consider the effects of the presence of knowledge spillovers.

results that follow can be derived from the previous propositions. However, a separate analysis is proposed here, using supermodularity techniques.

Consider, first, product market competition. The incentive instruments α_i^A and α_i^B are complementary to λ when product market competition is sufficiently intense and spillovers are not too high. When λ is high and β is low, the marginal impact on profits of each type of research is high, and the effects reinforce each other.

Proposition 3.6 *α_i^A and α_i^B are complementary in λ if $\lambda > \underline{\lambda}(\beta)$, with $\underline{\lambda}(\beta) \geq \frac{2}{3}$ and $\frac{d\underline{\lambda}(\beta)}{d\beta} > 0$.*

As for the complementarity between α_i^A and α_i^B, and changes in knowledge spillovers, the lower the intensity of competition λ, the less likely that expected surplus, $E(TS)$, is supermodular in α_i^A, α_i^B and β – i.e. $E(TS)$ is going to be supermodular for a smaller set of the other parameter values. When λ is low, if a firm provides high-powered incentive in one activity, it operates at lower cost, and then it has convenience to provide high-powered incentives to the other activity as well. In this case, as we argued before, the negative effect of spillover from basic research is limited (see Proposition 3.2 and 3.3).

Proposition 3.7 *α_i^A and α_i^B are complementary in β if $\lambda \to 0$.*

3.1.5 Discussion

The main insight from this first set of results is not only that such characteristics as product market competition and knowledge spillovers matter in the determination of incentives to scientists, but also that they interact in the impact they have on incentive provision. In addition to this theoretical insight, a major implication for empirical analysis is that the structure of the product market and the IP regimes need to be controlled for when assessing the determinants of scientists' pays and incentive structures. Cockburn et al. (2006), for example, find that incentives for basic and applied research are complementary in the pharmaceutical industry: when firms commit to high-powered incentives to obtain recognition in the scientific community, they also offer higher-powered rewards for applied activities. The authors use data at the level of research programs; arguably, different research programs refer to different final product markets, thus our model suggests an extension of the work of Cockburn et al., consisting of the estimate of the relation between basic and applied research incentives separately for each submarket, in order to account for potentially different competitive and knowledge-appropriability conditions.

In a study of the wage determination of software developers, Andersson et al. (2009) find that wages are more responsive to performance in more "risky" industry segments, where riskiness is measured in terms of the 90/50 ratio of product line sales per worker. The authors offer a sorting explanation for their results. Firms in highly risky environments benefit more from having star workers. In order to attract them, firms offer a better pay, both in terms of fixed and performance related-wage. Our results point to additional (though not necessarily mutually exclusive) explanations. A more "risky" industry segment might also be a more concentrated one. For example, the video game software developing/publishing segment, indicated by Andersson et al. as the riskiest in their sample, has experienced increased concentration over the 1990s, up to a four-firm concentration ration greater than 50% in the early 2000s (Williams 2002). The IT-software online journal *SoftwareMag.com* publishes a list of the biggest software companies. Among the 100 biggest companies of this survey, only two declare "Database" as their primary product line; eight indicate software for financial applications, and nine indicate infrastructure/networking software. Among these three segments, Andersson et al. indicate "networking" as the riskiest, and "database" as the least risky. In addition, intellectual property protection in software is relatively weak, and knowledge spillovers are pervasive.[14] If higher riskiness goes together with higher concentration and intellectual property protection is weak, then our model predicts that companies offer higher powered incentives in less competitive product lines.

3.2 Monetary wage and non-pecuniary benefits: a trade-off?

We now move to the analysis of the relationship between the non-monetary drivers of scientific effort, such as scientific curiosity of the desire to excel in the community of peers, and a firm's decision of the type of incentive contract to offer to scientists. In the model, the non-monetary motives are expressed by the parameter ρ in the scientists' utility function. As a direct effect, an increase in the researcher's taste for science makes effort in basic research more attractive; in turn, through its effect on the firm's size, this leads the firm to increase the power of the incentives both for basic and applied research. In other words, the firm prefers to reinforce the non-monetary incentives through the wage schedule. This mechanism leads to the following propositions:

Proposition 3.8 *Both α_E^A and α_E^B are increasing in ρ.*

[14] Graham and Mowery (2003) report that, until the early 1990s, the major form of IP protection for software was through copyright. A series of court rulings, however, have reduced the power of copyright in preventing imitation by rivals. In more recent years, companies have increasingly patented their software inventions. Since software patents have been used only recently, the absence of a prior art has made it difficult for examiners to assess the appropriateness of a patent application. Besides, patent systems around the world, in a typically global industry, have shown differing degrees of severity in accepting applications. It is reasonable to conclude that patents have only a limited role in the protection of software. Notice, also, that the majority of software patents are held by non-software companies. Finally, job hopping is widespread in the software industry, thus allowing ideas and possibly secrets to move from one company to another, together with people who carry these ideas (Fallick et al. 2006, Freedman 2006).

Proposition 3.9 *α_i^A,α_i^B and ρ are complementary.*

The presence of a taste for science ρ has also implications for determining the fixed component of wage, α^0. In the standard case, α^0 is simply determined by the participation constraint, which is binding in equilibrium. In our framework, it is interesting to study how the fixed wage varies with ρ. The effect is a-priori ambiguous. Higher ρ implies that the scientists obtain a higher benefit from basic research. At the same time, as from Proposition 3.8, the scientists exert higher effort in both applied and basic research, for which they must be compensated. It turns out that the first effect prevails, thus α_E^0 (the fixed wage in equilibrium) is always decreasing in ρ. This result is summarized in the next proposition:

Proposition 3.10 *α_E^0 is always decreasing in ρ.*

Last, we look at the relationship between the overall expected wage $\alpha_E^0+\alpha_E^A E(X^A)+ \alpha_E^B E(X^B)$ and the degree of non-monetary benefits. We show that for low levels of ρ, the expected wage is increasing in ρ, i.e. the effect on the piece rates prevails. For high ρ, examples both for the case in which the expected wage is increasing and for the case in which it is decreasing in ρ can be found.

Proposition 3.11 *The expected wage $\alpha_E^0+\alpha_E^A E(x_A)+ \alpha_E^B E(x_A)$ is increasing in ρ when ρ is small. $\alpha_E^0 + \alpha_E^A E(x_A)+ \alpha_E^B E(x_A)$ may be increasing or decreasing in ρ when ρ is high.*

3.2.1 Discussion

This second set of results, also, offer insights to empirical research. Again, we use some existing empirical studies to show the relevance of our results. Stern (2004) investigates whether the R&D orientation of firms leads scientists to accept lower wages. He finds that firms that allow their researchers to publish their findings, or even reward scientists for their publications, offer lower monetary wages. Stern concludes that researchers show a taste for science. The model in this paper is in line with this claim as it includes, through the parameter ρ, non-pecuniary benefits for company scientists when they engage in basic science. We show a negative relation between the taste for science and the fixed component of wage, but a positive relationship with piece rates. Furthermore, we show that the overall expected wage is increasing in ρ when ρ is not too high. Using Stern's terminology, we can claim that a "productivity effect" acts at the level of the performance-based component of wage, while a "preference effect," i.e. the willingness of a science-oriented researcher to give up money in exchange for science, acts on the fixed salary (which is what Stern is able to observe). Since Stern's empirical analysis is based on a sample of young researchers looking for their first job, and these scientists are likely to have both a high intrinsic motivation to science, our results directly point at his work.[15] An implication of our results, however, is also that it is important to analyze the different components of the wage separately, in order to properly assess the impact of each effect.

Our result on the positive relationship between monetary and non-monetary incentives offers yet a further interpretation to the findings of Andersson et al. (2009), previously described, on the positive effect of the riskiness of a sector and the power of incentives to software developers. These workers may also derive non-monetary benefits from their work (Lakhani and von Hippel 2003). If developers with higher non-monetary motivations prefer to work in more risky lines (because success may bring greater "fame" among peers, for example), then our model predicts that these workers will have steeper performance pay schemes.

In addition to providing novel theoretical insights and to interpreting empirical findings, the model also has a number of implications for managers and entrepreneurs. These further insights are discussed in the following Section.

4 Managerial implications: R&D organization and beyond

Providing incentives to corporate scientists is a complex problem that requires to consider the nature of the knowledge that scientists are expected to generate, the monetary and intrinsic motivations of researchers, and the competitive conditions in the markets where a firm operates. If a company is positioned so as to enjoy market power, cost-reducing efforts by its scientists are likely to have a sizeable impact on the level of profits. When competition is more intense, cost reduction might instead be crucial for survival, thus again leading firms to provide stronger incentives to scientists for process innovations. The latter case, however, depends also on the degree to which the knowledge produced by a firms's scientists spills over to rivals. If these spillovers are high, then incentivizing scientists too strongly results in offering an advantage to rivals. In an environment where knowledge flows easily, managers and entrepreneurs should be aware that the organizational responses to market competition may be different than in a world of more "private" knowledge. Conversely, the level of knowledge appropriability has a different impact in highly and weakly competitive markets. In the former type of markets, as said, low appropriability may offer an advantage to competitors which, in turn, backfires on the focal company. When competition on the product market is low, by

[15] Sauermann and Cohen (2007) document that scientists working in small entrepreneurial companies tend, in fact, to be younger and less risk averse than the average corporate scientist.

contrast, each firm is reinforced by the spillovers deriving from the other firm; this reinforcement, however, does not affect the profitability of the originating firms, since there is no direct interaction in the final market. Finally, scientists who are more eager to maintain their links to the scientific community even when employed by a firm, and are allowed by a firm to do so, are not necessarily "cheap," since it may be optimal for a firm to provide them with more powerful incentives and higher expected wages.

The above considerations are useful also to analyze how organizations motivate other types of workers. Just as in the case of firms dealing with researchers, such issues as competitive pressure, leakage of relevant information, multidimensional effort and multiple motivations are going to be of relevance for other professions within companies, and for other organizations. Examples include such industries as health care and advertising (Gaynor et al. 2005, Von Nordenflycht 2007), and such organizations as universities, hospitals, and the military.

5 Summary and directions for future research

The model of incentive provision to company scientists developed in this paper is based on four key characteristics of research activities. First, scientists engage in multiple, different activities when performing research, e.g. in (proprietary) applied and (open) basic research. Second, the knowledge produced through research activities is not perfectly appropriable. Third, scientists are responsive both to monetary incentives and to non-material motives, such as their reputation in the community of peers. Fourth, the provision of incentives depends on the conditions a firm faces in the product market, such as the intensity of competition.

We show that the strength of incentives for applied and basic research depends on the interaction of intensity of competition and degree of knowledge spillovers. Greater knowledge spillovers positively affect the provision of incentives only when competition is low, whereas in more competitive environments, the impact of higher knowledge spillovers on the incentive scheme is ambiguous. The relationship between the intensity of competition and the power of incentives to scientists is in general U-shaped, with the exact shape and slopes, again, crucially depending on the intensity of spillovers. An implication of these findings is that incentives for basic and applied research are complementary only if either competition or knowledge spillovers are low. We also show that the incentives for both applied and basic research increase with the non-pecuniary benefits that scientists obtain from basic research, while a trade-off between monetary pay and non-monetary rewards can occur at the level of the fixed salary.

These results carry implications for empirical research as well as for managerial practice. Empirical studies of the determinants of incentives to scientists need to account for such environmental conditions as the degree of product market competition and of appropriability of knowledge, and need to analyze separately different components of wages, e.g. fixed and contingent pays, since they might respond differently to certain changes. Similarly, firms need to look at their position in the product market, and at the knowledge appropriability conditions for different types of activities, when designing their internal R&D organization. Managers should also account for the non-monetary motivations of scientists.

A further application of our work is in the policy debate. Our analysis implies that IP protection rules should be determined in relation to the level of competition of each industry and that, in particular, antitrust legislation and IP protection are complementary instruments. When companies face lower competition on the final market, they have "nothing to fear" from low knowledge appropriability; instead, they find it even more profitable to motivate the performance of basic research by their scientists. Conversely, in industries where IP protection is very strong, competition on the product market should be particularly favored. These implications of the model lend support to a view of IP protection and antitrust laws as complementary. Ganslandt (2008) shows, in fact, that there is a strong, positive correlation, across countries, between strength of IP protection and effectiveness of antitrust regulations.

The analysis in this paper can be extended in a number of directions. A richer setup would consider firms differing in their focus on, or their efficiency in, different types of research, as well as scientists differing in their abilities and motivations. A further related extension would be to model the interaction between the incentive provision problem and the labor market for scientists. The incentive schemes would be devised so as to equalize returns across firms, and if firms and scientists are heterogeneous, matching dynamics would also be relevant (Besley and Ghatak 2005). The model, finally, focuses on *competition* among firms. Further developments would also explore how the incentive provision problem changes when firms cooperate in R&D.[16] In turn, the comparison between competitive and cooperative outcomes is a natural step in the analysis of the welfare consequences in addition to some of the conjectures made in the paper.

[16] See, among others, D'Aspremont and Jacquemin (1988), Lin and Saggi (2002), and Rosenkranz (2003).

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A Notation and figures

Players	
$i,\ j$	Subscripts indicating, respectively, firm i and firm j, as well as scientist i (agent of firm i) and scientist j (agent of firm j)
Choice variables	
α_i^A,α_i^B	Wage coefficient related to the performance measures X^A and X^B (see below), chosen by the firms
α_i^0	Fixed component of the scientists' wage, chosen by the firms
$e_i^A,\ e_i^B$	Effort levels in applied and basic research, respectively, chosen by the scientists
q_i	Product quantity level, chosen by the firms
Payoffs parameters	
$\Pi_i,\ \Pi_j$	Firms' profits
w_i	Scientist's wage
ρ	Scientists' non monetary benefits per unit of basic research effort
γ	Effort cost parameter
r	Coefficient of absolute risk aversion in the scientist's utility function
$X_i^A,\ X_i^B$	Performance measures for applied and basic effort, respectively, used by the firms to determine the scientists' wage
c_i	Marginal cost of production
c	Fixed component of the marginal cost function
$\beta \in [0,1]$	Degree with which scientist j's basic research effort reduces the marginal cost of firm i (indicator of the intensity of knowledge spillovers)
Demand parameters	
p_i	Product price
A	Maximum willingness to pay by consumers
$\lambda \in [0,1]$	Degree of substitutability between the products of the two firms (indicator of competitive pressure)

Table 1: Summary of the notation used in the model. The choice variables and parameters are reported only for firm i, for simplicity.

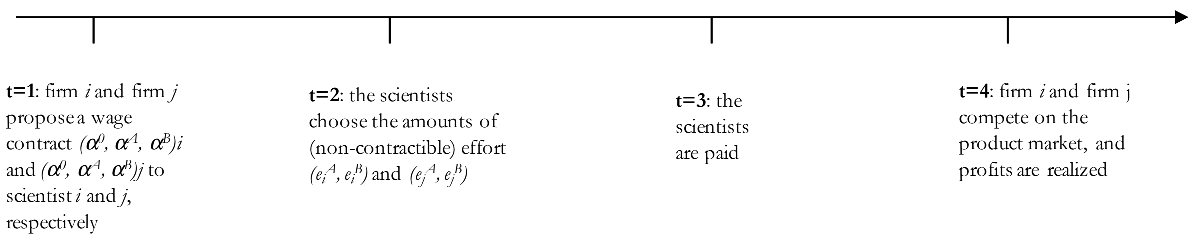

Figure 1: The game's timeline

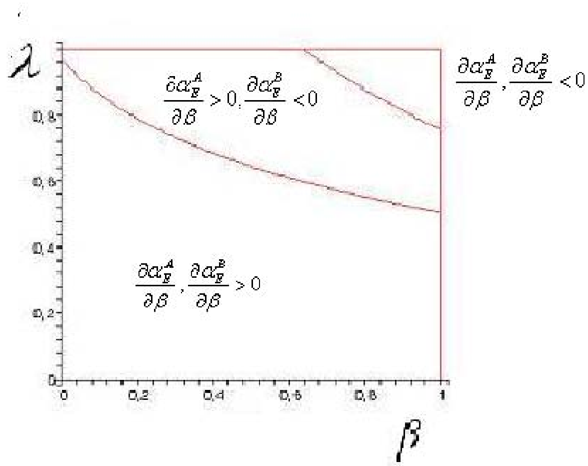

Figure 2: The impact of knowledge spillovers on the strength of incentives, for different combinations of knowledge spillovers and product market competition intensities. The examples are built using the following values: $A = 2$; $c = 1$, $\gamma = 1.5$, $\rho = .2$.

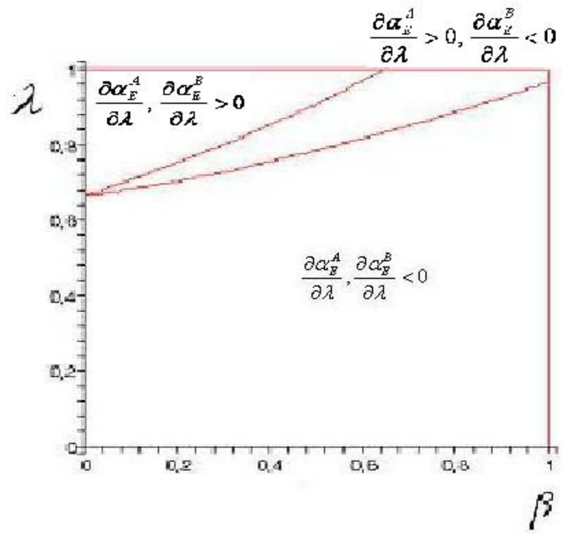

Figure 3: The impact of competitive pressure on the strength of incentives, for different combinations of knowledge spillovers and product market competition intensities. The examples are built using the following values: $A = 2$; $c = 1$, $\gamma = 1.5$, $\rho = .2$.

B Proofs

Proof of Proposition 3.1 The proof is immediate from taking the ratio between the two equilibrium piece rates:

$$\frac{\alpha_E^A}{\alpha_E^B} = \frac{2}{2-\beta\lambda}.$$

Proof of Proposition 3.2 and Corollary 3.2.1 If we differentiate α_E^A with respect to β, we obtain:

$$\frac{\partial \alpha_E^A}{\partial \beta} = \frac{16\rho\left[\gamma k - 4 - 2(1+\beta)(2-\beta\lambda)\right] + 32\left[\gamma(A-c) + \rho(1+\beta)\right]\left[2 - 2\beta\lambda - \lambda\right]}{\left[\gamma k - 4 - 2(1+\beta)(2-\beta\lambda)\right]^2}.$$

Notice that $[\gamma k - 4 - 2(1+\beta)(2-\beta\lambda)] > 0$ (since it is the denominator of α_E^A), while $32\,[\,\gamma(A-c) + \rho\gamma(1+\beta)] * (2 - 2\beta\lambda - \lambda)$ is positive if $2 - 2\beta\lambda - \lambda > 0$. It follows that, if $\lambda < \frac{2}{1+2\beta}$, then $\frac{\partial \alpha_E^A}{\partial \beta} > 0$, from which the Corollary is obtained.

We now investigate the behavior of $\frac{\partial \alpha_E^A}{\partial \beta}$ as a function of λ. For $\lambda = 0$ we know that $\frac{\partial \alpha_E^A}{\partial \beta} > 0$. If we compute $\frac{\partial \alpha_E^A}{\partial \beta \partial \lambda}$ we obtain:

$$\frac{\partial \alpha_E^A}{\partial \beta \partial \lambda} = \frac{\begin{array}{c} \{16\rho\left[\gamma(\lambda+2)(2-3\lambda)-2(1+2\beta)\beta\right]-32(A-c)\gamma(1+2\beta)\} * \\ \left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right]^2 \\ -\left\{32\left[\gamma(A-c)\right](2-2\beta\lambda-\lambda)+16\rho\left[\gamma k-4-2(1+\beta)^2\lambda\right]\right\} \\ *2\left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right] \\ \left[\gamma(\lambda+2)(2-3\lambda)+2(1+\beta)\beta\right] \end{array}}{\left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right]^4}.$$

Overall the sign is ambiguous, since the three quantities

$$16\rho\left[\gamma(\lambda+2)(2-3\lambda)-2(1+2\beta)\beta\right]-32(A-c)\gamma(1+2\beta),$$
$$32\left[\gamma(A-c)\right](2-2\beta\lambda-\lambda)+16\rho\left[\gamma k-4-2(1+\beta)^2\lambda\right], \text{ and}$$
$$\left[\gamma(\lambda+2)(2-3\lambda)+2(1+\beta)\beta\right]$$

all have ambiguous signs. However, when $\frac{\partial \alpha_E^A}{\partial \beta}=0$, the sign of $\frac{\partial \alpha_E^A}{\partial \beta \partial \lambda}$ is the sign of:

$$\{16\rho\left[\gamma(\lambda+2)(2-3\lambda)-2(1+2\beta)\beta\right]-32(A-c)\gamma(1+2\beta)\}. \tag{19}$$

Expression (19) is negative for $\lambda \leq \frac{2}{3}$, which is a necessary condition to have $\frac{\partial \alpha_E^A}{\partial \beta}=0$. This implies that in any point in which the derivative is 0, the graph cuts the horizontal axis "from above." In turn, together with $\frac{\partial \alpha_E^A}{\partial \beta}>0$ when $\lambda=0$, this implies that the value of λ for which $\frac{\partial \alpha_E^A}{\partial \beta}=0$ is unique, if it exists. Then, there are two possible cases: i) $\frac{\partial \alpha_E^A}{\partial \beta}$ is first positive and then negative with respect to λ; ii) $\frac{\partial \alpha_E^A}{\partial \beta}$ is always positive. The first part of the Proposition follows from this.

Define now λ_A^* as the unique solution to $\frac{\partial \alpha_E^A}{\partial \beta}=0$. In order to show that λ_A^* is decreasing in β, we can apply the implicit function theorem. Consider:

$$H^A(\beta,\lambda)=32\left[\gamma(A-c)\right](2-2\beta\lambda-\lambda)+16\rho\left[\gamma k-4-2(1+\beta)^2\lambda\right];$$

the solution of $H^A(\beta,\lambda)=0$ is the set of values for which $\frac{\partial \alpha_E^A}{\partial \beta}=0$. Denote with (λ_A^*, β_A^*) a solution pair. Then, using the implicit function theorem, we can derive $\frac{\partial \lambda_A^*}{\partial \beta_A^*}$ as

$$\frac{\partial \lambda_A^*}{\partial \beta_A^*}=-\frac{\frac{\partial \alpha_E^A}{\partial \beta^2}\Big|_{\frac{\partial \alpha_E^A}{\partial \beta}=0}}{\frac{\partial \alpha_E^A}{\partial \beta \partial \lambda}\Big|_{\frac{\partial \alpha_E^A}{\partial \beta}=0}}.$$

We just showed that $\frac{\partial \alpha_E^A}{\partial \beta \partial \lambda}\Big|_{\frac{\partial \alpha_E^A}{\partial \beta}=0}<0$. As far as $\frac{\partial \alpha_E^A}{\partial \beta^2}\Big|_{\frac{\partial \alpha_E^A}{\partial \beta}=0}$ is concerned, differentiation yields:

$$\frac{\partial \alpha_E^A}{\partial \beta^2} = \frac{\begin{array}{c}\{-64\lambda\left[\gamma(A-c)+(1+\beta)\rho\right]\}\left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right]^2 \\ -\left\{32\left[\gamma(A-c)\right](2-2\beta\lambda-\lambda)+16\rho\left[\gamma k-4-2(1+\beta)^2\lambda\right]\right\} \\ *2\left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right] \\ \left[2(2-2\beta\lambda-\lambda)\right]\end{array}}{\left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right]^4},$$

whose sign, for $\frac{\partial \alpha_E^A}{\partial \beta} = 0$, is the sign of $-64\lambda\left[\gamma(A-c)+(1+\beta)\rho\right]$, which is negative. Then, $\frac{\partial \lambda_A^*}{\partial \beta_A^*} < 0$, from which the second part of the Proposition follows.

Proof of Proposition 3.3 and Corollary 3.3.1 Differentiating α_E^B with respect to β, we obtain:

$$\frac{\partial \alpha_E^B}{\partial \beta} = \frac{\begin{array}{c}\{8\rho(2-\beta\lambda)-8\lambda\left[\gamma(A-c)+\rho(1+\beta)\right]\}\left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right] \\ +16\left[\gamma(A-c)+\rho(1+\beta)\right](2-2\beta\lambda-\lambda)(2-\beta\lambda)\end{array}}{\left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right]^2}, \tag{20}$$

whose sign is ambiguous. However, if $(2-2\beta\lambda-\lambda)<0$ (i.e., $\lambda > \frac{2}{1+2\beta}$), then $\frac{\partial \alpha_E^B}{\partial \beta} < 0$, from which the Corollary follows.

We study now the behavior of $\frac{\partial \alpha_E^B}{\partial \beta}$ as a function of λ. For $\lambda = 0$, we have $\frac{\partial \alpha_E^B}{\partial \beta} > 0$. Differentiating, we obtain:

$$\frac{\partial \alpha_E^B}{\partial \beta \partial \lambda} = \frac{\begin{array}{c}\left\{\begin{array}{c}8\rho\left[(-2\beta-1)(\gamma k-4)+(2-2\beta\lambda-\lambda)\gamma(\lambda+2)(2-3\lambda)\right] \\ -8\gamma(A-c)\left[\gamma k-4+\lambda(\lambda+2)(2-3\lambda)+4\beta(2-\beta\lambda)\right]\end{array}\right\}* \\ \left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right]^2 \\ -8\rho(2-2\beta\lambda-\lambda)(\gamma k-4)-8\gamma(A-c)\left[\lambda(\gamma-4)-2(2-\beta\lambda)^2\right]* \\ 2\left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right]* \\ \left[(\lambda+2)(2-3\lambda)+2(1+\beta)\beta\right]\end{array}}{\left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right]^4}. \tag{21}$$

The sign of (21) is ambiguous. However, we prove that $\frac{\partial \alpha_E^B}{\partial \beta \partial \lambda} < 0$ when $\frac{\partial \alpha_E^B}{\partial \beta} = 0$. In this case, the sign of $\frac{\partial \alpha_E^B}{\partial \beta \partial \lambda}$ is the sign of:

$$\left\{\begin{array}{c}8\rho\left[(-2\beta-1)(\gamma k-4)+(2-2\beta\lambda-\lambda)\gamma(\lambda+2)(2-3\lambda)\right] \\ -8\gamma(A-c)\left[\gamma k-4+\lambda(\lambda+2)(2-3\lambda)+4\beta(2-\beta\lambda)\right]\end{array}\right\}. \tag{22}$$

Notice, from above considerations, that in order to have $\frac{\partial \alpha_E^B}{\partial \beta} = 0$, it must be $(2-2\beta\lambda-\lambda)>0$. Then if $(2-3\lambda)<0$, the above quantity is negative, and the proof is given. Assume instead that $(2-3\lambda)>0$ and that $\left[(-2\beta-1)(\gamma k-4)+(2-2\beta\lambda-\lambda)\gamma(\lambda+2)(2-3\lambda)\right]>0$ (which would otherwise imply that (22) is negative). By assumption, $A-c \geq \rho$. Thus, if

$$\gamma\left[\gamma k-4+\lambda(\lambda+2)(2-3\lambda)+4\beta(2-\beta\lambda)\right] > (-2\beta-1)(\gamma k-4)+(2-2\beta\lambda-\lambda)\gamma(\lambda+2)(2-3\lambda),$$

then we proved our result. Simplifying, the expression, we obtain:

$$(\gamma+1+2\beta)(\gamma k-4)-\gamma(\lambda+2)(2-3\lambda)(2-2\beta\lambda)+4\beta\gamma(2-\beta\lambda)>0. \tag{23}$$

We note the following. $(\gamma+1+2\beta)$ is increasing in β. $(\gamma k-4)$ is increasing in λ when $\lambda<\frac{2}{3}$, as we assumed. $(\lambda+2)(2-3\lambda)(2-2\beta\lambda)>0$ is decreasing in λ since $\frac{\partial(\lambda+2)(2-3\lambda)}{\partial\lambda}=2-3\lambda-3\lambda-6<0$, and is decreasing in β. Finally, $\frac{\partial 4\beta\gamma(2-\beta\lambda)}{\partial\beta}=\gamma(2-2\beta\lambda)>0$, since $(2-2\beta\lambda-\lambda)>0$. This implies that if (23) is positive for $\beta=\lambda=0$, then our claim follows. For $\beta=\lambda=0$, $(\gamma+1)(8\gamma-4)-8\gamma>0$, since $\gamma>1$.

We proved that $\frac{\partial\alpha_E^B}{\partial\beta\partial\lambda}<0$ when $\frac{\partial\alpha_E^B}{\partial\beta}=0$. This means that, in any point in which the derivative is 0, the graph cuts "from above" the horizontal axis. In turn, together with $\frac{\partial\alpha_E^B}{\partial\beta}>0$ in $\lambda=0$, this implies that the value of λ for which $\frac{\partial\alpha_E^B}{\partial\beta}=0$ is unique, if existing. Then, there are two possible cases: i) $\frac{\partial\alpha_E^B}{\partial\beta}$ is first positive and then negative with respect to λ; ii) $\frac{\partial\alpha_E^B}{\partial\beta}$ is always positive. The first part of the Proposition follows.

Define λ_B^* as the unique solution to $\frac{\partial\alpha_E^B}{\partial\beta}=0$. In order to show that λ_B^* is decreasing in β, we can apply, again, the implicit function theorem. Consider:

$$H^B(\beta,\lambda)=8\rho(2-2\beta\lambda-\lambda)(\gamma k-4)-8\gamma(A-c)\left[\lambda(\gamma-4)-2(2-\beta\lambda)^2\right]; \tag{24}$$

the solution of $H^B(\beta,\lambda)=0$ is the set of values for which $\frac{\partial\alpha_E^B}{\partial\beta}=0$. Denote with (λ_B^*,β_B^*) a solution pair. Then, using the implicit function theorem, we derive $\frac{\partial\lambda_B^*}{\partial\beta_B^*}$:

$$\frac{\partial\lambda_B^*}{\partial\beta_B^*}=-\frac{\frac{\partial\alpha_E^B}{\partial\beta^2}\Big|_{\frac{\partial\alpha_E^B}{\partial\beta}=0}}{\frac{\partial\alpha_E^B}{\partial\beta\partial\lambda}\Big|_{\frac{\partial\alpha_E^B}{\partial\beta}=0}}.$$

We just showed that $\frac{\partial\alpha_E^B}{\partial\beta^2}\big|_{\frac{\partial\alpha_E^B}{\partial\beta}=0}<0$. As for $\frac{\partial\alpha_E^B}{\partial\beta^2}\big|_{\frac{\partial\alpha_E^B}{\partial\beta}=0}$, computing $\frac{\partial^2\alpha_E^B}{\partial\beta^2}=0$ we obtain:

$$\frac{\partial^2\alpha_E^B}{\partial\beta^2}=\frac{\begin{array}{c}[-16\rho\lambda(\gamma k-4)-16\lambda\gamma(A-c)(2-\beta\lambda)]\,[\gamma k-4-2(1+\beta)(2-\beta\lambda)]^2+\\ \left[8\rho(2-2\lambda\beta-\lambda)(\gamma k-4)-8\gamma(A-c)(\lambda(\gamma k-4)-2(2-\beta\lambda)^2\right]*\\ 2(\gamma k-4-2(1+\beta)(2-\beta\lambda))(2(2-2\beta\lambda-\lambda))\end{array}}{[\gamma k-4-2(1+\beta)(2-\beta\lambda)]^4}. \tag{25}$$

If $\frac{\partial\alpha_E^B}{\partial\beta}=0$, then the sign of $\frac{\partial^2\alpha_E^B}{\partial\beta^2}$ is the sign of $[-16\rho\lambda(\gamma k-4)-16\lambda\gamma(A-c)(2-\beta\lambda)]$, which is always negative. The second part of the Proposition follows. Finally, to show that $\lambda_B^*\leq\lambda_A^*$ note that for $2-2\beta\lambda-\lambda=0$, $\frac{\partial\alpha_E^A}{\partial\beta}>0$, which implies $\lambda_A^*>\frac{2}{1+2\beta}$, and $\frac{\partial\alpha_E^B}{\partial\beta}<0$, which implies $\lambda_B^*<\frac{2}{1+2\beta}$.

Proof of Proposition 3.4 Differentiating α_E^A with respect to λ, we obtain:

$$\frac{\partial\alpha_E^A}{\partial\lambda}=-\frac{16\left[\gamma(A-c)+\rho(1+\beta)\right]\left[\gamma(\lambda+2)(2-3\lambda)+2(1+\beta)\beta\right]}{\left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right]^2}, \tag{26}$$

which has the same sign as $-\left[\gamma(\lambda+2)(2-3\lambda)+2(1+\beta)\beta\right]$. Consequently, we have $\frac{\partial\alpha_E^A}{\partial\lambda}>0$ if $\lambda>\frac{\sqrt{16+\frac{6\beta(1+\beta)}{\gamma}}-2}{3}=\lambda_A^{**}$. It is immediate to verify that λ_A^{**} is increasing in β. Notice that it also possible that the derivative is always negative. This occurs when $\sqrt{16+6\frac{\beta(1+\beta)}{\gamma}}-2>3$, i.e., $\gamma<\frac{2}{3}\beta(1+\beta)$.

Proof of Proposition 3.5 Differentiating α_E^B with respect to λ, we obtain:

$$\frac{\partial\alpha_E^B}{\partial\lambda}=\frac{8\left[\gamma(A-c)+\rho(1+\beta)\right]\left\{\begin{array}{c}-\beta\left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right]\\-(2-\beta\lambda)\left[\gamma(\lambda+2)(2-3\lambda)+2(1+\beta)\beta\right]\end{array}\right\}}{\left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right]^2}, \tag{27}$$

which can be simplified to:

$$\frac{\partial\alpha_E^B}{\partial\lambda}=\frac{8\left[\gamma(A-c)+\rho(1+\beta)\right]\left\{-\beta\left(\gamma k-4\right)-(2-\beta\lambda)\gamma(\lambda+2)(2-3\lambda)\right\}}{\left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right]^2}. \tag{28}$$

We study now the sign of $\frac{\partial\alpha_E^B}{\partial\lambda}$ as a function of λ. From (28), we have $\frac{\partial\alpha_E^B}{\partial\lambda}<0$ in $\lambda=0$. Computing $\frac{\partial^2\alpha_E^B}{\partial\lambda^2}$ we obtain:

$$\frac{\partial^2\alpha_E^B}{\partial\lambda^2}=\frac{8\left[\gamma(A-c)+\rho(1+\beta)\right]\left\{\begin{array}{c}\left[-\gamma(2-\beta\lambda)(-4-6\lambda)\right]\left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right]^2-\\\left[-\beta(\gamma k-4)-(2-\beta\lambda)\gamma(\lambda+2)(2-3\lambda)\right]*\\2\left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right]*\gamma(\lambda+2)(2-3\lambda)+2(1+\beta)\beta\end{array}\right\}}{\left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right]^4} \tag{29}$$

If $\frac{\partial\alpha_E^B}{\partial\lambda}=0$, the sign of $\frac{\partial^2\alpha_E^B}{\partial\lambda^2}$ is the sign of $-\gamma(2-\beta\lambda)(-4-6\lambda)$, then $\frac{\partial^2\alpha_E^B}{\partial\lambda^2}>0$. Then, in any point in which the derivative is 0, the graph cuts from "below" the horizontal axis. This implies that the value of λ for which $\frac{\partial\alpha_E^B}{\partial\lambda}=0$ is unique, if existing. Then, there are two possible cases: i) $\frac{\partial\alpha_E^B}{\partial\lambda}=0$ is first negative, then positive; ii) $\frac{\partial\alpha_E^B}{\partial\lambda}=0$ is always negative. The first part of Proposition follows.

In order to show that λ_B^{**} is increasing in β, the implicit function theorem is applied again. Consider:

$$W^B(\beta,\lambda)=\left\{-\beta\left(\gamma k-4\right)-(2-\beta\lambda)\gamma(\lambda+2)(2-3\lambda)\right\};$$

the solution of $W^B(\beta,\lambda)=0$ is the set of values for which $\frac{\partial\alpha_E^B}{\partial\lambda}=0$. Denote with $(\lambda_B^{**},\beta_B^{**})$ a solution pair. Then, using the implicit function theorem, we derive $\frac{\partial\lambda_B^{**}}{\partial\beta_B^{**}}$:

$$\frac{\partial\lambda_B^{**}}{\partial\beta_B^{**}}=-\frac{\frac{\partial\alpha_E^B}{\partial\lambda\partial\beta}\Big|_{\frac{\partial\alpha_E^B}{\partial\lambda}=0}}{\frac{\partial\alpha_E^B}{\partial^2\lambda}\Big|_{\frac{\partial\alpha_E^B}{\partial\lambda}=0}}.$$

Thus, $\frac{\partial\alpha_E^B}{\partial\lambda^2}\Big|_{\frac{\partial\alpha_E^B}{\partial\lambda}=0}>0$. Regarding $\frac{\partial\alpha_E^B}{\partial\lambda\partial\beta}\Big|_{\frac{\partial\alpha_E^B}{\partial\lambda}=0}$, we obtain:

$$\frac{\partial \alpha_E^B}{\partial \lambda \partial \beta} = \frac{\begin{array}{c}\left\{\begin{array}{c} 8\left[\gamma(A-c)+\rho(1+\beta)\right]\left[-\gamma k+\lambda\gamma(\lambda+2)(2-3\lambda)\right] \\ +8\rho\left[-\beta(\gamma k-4)-(2-\beta\lambda)\gamma(\lambda+2)(2-3\lambda)\right]\end{array}\right\} * \\ \left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right]^2 + \\ +8\left[\gamma(A-c)+\rho(1+\beta)\right]\left\{\left[-\beta(\gamma k-4)-(2-\beta\lambda)\gamma(\lambda+2)(2-3\lambda)\right]\right\} * \\ 2\left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right] * 2(2-2\beta\lambda-\lambda)\end{array}}{\left[\gamma k-4-2(1+\beta)(2-\beta\lambda)\right]^4}. \tag{30}$$

When $\frac{\partial \alpha_E^B}{\partial \lambda} = 0$, the sign of $\frac{\partial \alpha_E^B}{\partial \lambda \partial \beta}$ is the sign of $\left[-\gamma k+\lambda\gamma(\lambda+2)(2-3\lambda)\right]$. After some manipulations we obtain:

$$\left[-\gamma k+\lambda\gamma(\lambda+2)(2-3\lambda)\right] = -\gamma(\lambda+2)(4-4\lambda^2+2\lambda) < 0,$$

from which the Proposition follows.

Finally, in order to show that $\lambda_B^{**} \leq \lambda_A^{**}$, we show that, if $\frac{\partial \alpha_E^A}{\partial \lambda} < 0$, then $\frac{\partial \alpha_E^B}{\partial \lambda} < 0$,which in turn implies the claim. In fact, if $\frac{\partial \alpha_E^A}{\partial \lambda} < 0$, then $\left[\gamma(\lambda+2)(2-3\lambda)+2(1+\beta)\beta\right] > 0$, which from (27) implies $\frac{\partial \alpha_E^B}{\partial \lambda} < 0$. We have $\lambda_B^{**} = \lambda_A^{**}$ when $\beta = 0$.

Proof of Proposition 3.6 If we compute the cross-derivatives of the total surplus function TS with respect to λ, we obtain:

$$\begin{aligned} \frac{\partial^2 E(TS)}{\partial \alpha_i^A \partial \lambda} &= \frac{\partial q_i}{\partial \lambda}\frac{4}{\gamma(\lambda+2)(\lambda-2)} + \frac{q_i}{\gamma}\frac{8\lambda}{(4-\lambda^2)^2} > 0; \\ \frac{\partial^2 E(TS)}{\partial \alpha_i^B \partial \lambda} &= \frac{\partial q_i}{\partial \lambda}\frac{4}{\gamma(\lambda+2)(\lambda-2)} + \frac{q_i}{\gamma}\left[\frac{8(\lambda-\beta)}{(4-\lambda^2)^2}\right] > 0. \end{aligned}$$

Under symmetry ($c_i = c_j$), we get $\frac{\partial q_i}{\partial \lambda} = -\frac{(A-c)}{(\lambda+2)}$. Notice that $q_i > \frac{(A-c)}{(\lambda+2)}$ and $\lim_{\gamma\to\infty} q_i = \frac{(A-c)}{(\lambda+2)}$. Then, supermodularity holds for all γ if:

$$2\lambda > (2-\lambda);$$

$$4(\lambda-\beta) > (2-\beta\lambda)(2-\lambda).$$

The first inequality is satisfied if $\lambda > \frac{2}{3}$. As for the second inequality, we define:

$$Z(\lambda,\beta) = 4(\lambda-\beta) - (2-\beta\lambda)(2-\lambda),$$

and we obtain:

$$\begin{aligned}\frac{\partial Z(\beta,\lambda)}{\partial\lambda} &= 4+\beta(2-\lambda)+(2-\beta\lambda)>0;\\ Z(\lambda,\beta)|_{\beta=0} &= 6\lambda-4;\text{ and}\\ \frac{\partial\lambda}{\partial\beta} &= \frac{8-4\lambda+4\beta\lambda}{12+4\beta-4\beta\lambda}>0,\end{aligned}$$

where $\frac{\partial\lambda}{\partial\beta}$ is obtained using Dini's theorem on the implicit function $Z(\lambda,\beta)$. These results together imply that $\frac{\partial^2 E(TS)}{\partial\alpha_i^B\partial\lambda}>0$ when $\lambda>\underline{\lambda}(\beta)$, with $\underline{\lambda}(\beta)\geq\frac{2}{3}$ and $\frac{d\underline{\lambda}(\beta)}{d\beta}>0$. Since this condition is stricter than $\lambda>\frac{2}{3}$, we can derive the claim.

Proof of Proposition 3.7 From (15) and (16), respectively, we obtain, after invoking symmetry:

$$\frac{\partial^2 E(TS)}{\partial\alpha_i^A\partial\beta} = \frac{(\alpha_i^B+\rho)}{k}\frac{4}{\gamma}\geq 0 \tag{31}$$

$$\frac{\partial^2 E(TS)}{\partial\alpha_i^B\partial\beta} = \frac{(\alpha_i^B+\rho)}{k}\left[\frac{2(2-\beta\lambda)}{\gamma}\right]-q_i\left[\frac{2\lambda}{\gamma(2-\lambda)(2+\lambda)}\right]. \tag{32}$$

For $\lambda\to 0$, (32) is positive, so that we have the claim.

Proof of Proposition 3.8 The proof is immediate by inspection of the expressions (17) and (18), since ρ appears only in the two numerators, which are both increasing in ρ.

Proof of Proposition 3.9 The proposition derives immediately from Proposition 3.8. We can also see that:

$$\frac{\partial E(TS)}{\partial\alpha_i^A\partial\rho}=2\left[\frac{1+\beta}{\gamma(2+\lambda)}\right]\left[\frac{2}{\gamma(2-\lambda)(2+\lambda)}\right]>0;$$

$$\frac{\partial E(TS)}{\partial\alpha_i^B\partial\rho}=2\left[\frac{1+\beta}{\gamma(2+\lambda)}\right]\left[\frac{2-\beta\lambda}{\gamma(2-\lambda)(2+\lambda)}\right]>0.$$

Proof of Proposition 3.10 In equilibrium, the agent's participation constraint binds:

$$E(U_i)=\alpha_E^0+\alpha_E^A\left(\frac{\alpha_E^A}{\gamma}\right)+\alpha_E^B\left(\frac{\alpha_E^B+\rho}{\gamma}\right)+\rho\left(\frac{\alpha_E^B+\rho}{\gamma}\right)-\frac{\gamma\left(\frac{\alpha_E^A}{\gamma}\right)^2}{2}-\frac{\gamma\left(\frac{\alpha_E^B+\rho}{\gamma}\right)^2}{2}=\overline{u},$$

where the equilibrium values for efforts are substituted into the expression. Simplifying the expression, we are left with:

$$E(U_i) = \alpha_E^0 + \frac{\left(\alpha_E^A\right)^2}{2\gamma} + \frac{\left(\alpha_E^B\right)^2}{2\gamma} + \frac{\rho^2}{2\gamma} + \frac{\rho\alpha_E^B}{\gamma}. \tag{33}$$

The quantity $\frac{\left(\alpha_E^A\right)^2}{2\gamma} + \frac{\left(\alpha_E^B\right)^2}{2\gamma} + \frac{\rho^2}{2\gamma} + \frac{\rho\alpha_E^B}{\gamma}$ is increasing in ρ since all its terms are increasing in ρ. As a consequence, α_E^0, the fixed component of wage, is decreasing in ρ in order for $E(U_i)$ to be constant.

Proof of Proposition 3.11 In equilibrium, $E(w) = \overline{u} + \frac{\left(\alpha_E^A\right)^2}{2\gamma} + \frac{\left(\alpha_E^B\right)^2}{2\gamma} - \frac{\rho^2}{2\gamma}$. Differentiating with respect to ρ, we obtain $\frac{\partial E(w)}{\partial \rho} = \gamma(1+\beta)\alpha_A + \gamma(1+\beta)\alpha_B - \rho$, which is positive for $\rho \to 0$. An example for which $\frac{\partial E(w)}{\partial \rho}$ is always increasing in ρ is $A = 2, c = 1, \lambda = 1, \beta = 0.5, \gamma = 1.5$, from which we get $\frac{\partial E(w)}{\partial \rho} = 1.5 + 0.85\rho$. An example for which $\frac{\partial E(w)}{\partial \rho}$ is decreasing in ρ for high ρ is $A = 2,\ c = 1,\ \lambda = 0.2, \beta = 0.5, \gamma = 5$, from which we get $\frac{\partial E(w)}{\partial \rho} = 0.0398 - 0.1880\rho$.