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Knowledge Spillovers, Competition, and R&D Incentive Contracts[*]

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Abstract

This paper models the optimal provision of incentives to corporate scientists, within an environment where effort is multidimensional, firms compete on the product market, knowledge spills over across companies, and scientists have both monetary and non-monetary motivations. The simultaneous consideration of these aspects generates a number of novel results. First, knowledge spillovers lead firms to soften incentives in order not to benefit competitors, but only when product market competition is high. By 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, and the region where the relationship is positive is smaller the higher the knowledge spillovers. Finally, both the incentives for applied and basic research increase with non-pecuniary benefits scientists obtain from basic research, while a trade-off between monetary pay and non-monetary rewards may occur at the level of the fixed salary. These results provide a novel interpretation of some observed R&D organizational choices by companies, offer insights for the management of scientific and other creative workers, and have implications for public policy.

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Introduction

Managing scientific workers and defining effective incentives for them has long been a challenge for business organizations, and is considered a key determinant of competitive success. Large established companies struggle to attract and provide strong incentives to top scientists, in order to keep at pace with scientific and technological advances. New entrepreneurial companies in high-tech and science-based sectors, in particular, are often founded by academic scientists, or are built around their discoveries. The survival itself of these ventures depends on their ability to attract and productively manage talented scientists.[1] At a time of tighter public budget constraints for several public research agencies (Bridges 2006), moreover, companies might be called on to increase their role in the production of knowledge, including the performance of basic research. Understanding the challenges companies have in the organization of innovative activities, and in particular in providing incentives to scientific workers, is therefore of importance for entrepreneurs and managers, as well as for policy makers.

The empirical literature on the provision of incentives to corporate scientists has focused on some specific aspects of this organizational problem. Stern (2004), for example, hypothesizes (and empirically finds) a negative relationship between the wage corporate scientists receive, and whether they are allowed and pursue their own research agenda in addition to the firm's projects, and to publish. This negative relationship is interpreted as consistent with the presence of a "taste for science" for which scientists are willing to pay in terms of lower monetary salary. Sauermann and Cohen (2007a) provide evidence on the positive impact of both pecuniary and non-pecuniary motivations of scientists on the innovative performance of companies. Cockburn et al. (2006) focus on the multitask nature of scientific research, e.g. the performance of basic and applied research activities. They argue that firms try to define incentive mechanisms in order to balance the performance of these activities. The incentive instruments, moreover, are complementary, i.e. they co-move in the same directions following changes in other relevant environmental conditions.

Little effort has been made, however, to elaborate theoretical frameworks in order to analyze the major, peculiar challenges that companies encounter in motivating scientific workers, to assess whether the available evidence on specific contexts is more broadly generalizable and applicable to other environments, and ultimately to inform empirical scholars as well as managers and policy makers. The aim of this paper is to propose such a theory. We contend that the provision of incentives to scientists needs to be analyzed as in relation to two broader environmental conditions: competition among firms in the product market, and spillovers of knowledge across companies. Furthermore, scientists' heterogeneous motivations, both monetary and non-monetary, must be taken into account.

A model is proposed, where two firms compete in an industry by offering differentiated products.

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[1] See Leslie (1980), Dennis (1987), Henderson and Cockburn (1994), Zucker and Darby (1995), Lamoreux and Sokoloff (1999), Lacetera et al. (2004), Lerner and Wulf (2006), Andersson et al. (2006), Lacetera (2007), Sauermann and Cohen (2007).

Each firm is composed of an owner and a scientist. The owners are in charge of choosing quantities (i.e. competition is à la Cournot), while the scientists are in charge of choosing two types of cost-reducing efforts. The two efforts differ in two respects: 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 it spills over to the rival firm. Efforts are not observed by the owner, who offers to the scientists a wage contract contingent on observable signals. The signals can include, for example, patents and scientific articles. A recent literature has indeed documented that even profit-oriented organization let their scientists publish their research, and reward them on the basis of their standing in the community of peers, as expressed for example by their publication record.[2] The model, therefore, embeds the incentive provision problem for corporate scientists in an environment where research activities are multidimensional, knowledge spillovers occur, scientists have multiple motivations, and firms compete on the product market.

The model produces three main sets of results, characterizing the optimal (linear) contract for the scientists. The first set of result concerns the relative strength of incentives for applied and basic research, as a function of the level of competition and knowledge spillovers. We obtain that the relative strength of incentives for applied research is increasing in the level of knowledge spillovers, and more so when competition among the firms is higher. For the higher is knowledge spillovers, the higher is the cost of providing incentives for basic research, since this benefits the competitor as well.

The second set of results concerns instead the absolute strength of incentives, again as a function of competition and spillovers. The effects of knowledge spillovers on the provision of incentives depend crucially on the competitive conditions in the product market. Greater knowledge spillovers positively affect the provision of incentives only when competition is low: in this case, providing strong incentives does not benefit rivals so much. In more competitive environments, the impact of higher knowledge spillovers on the incentive scheme is ambiguous, since providing stronger incentives to R&D workers can hurt the firm while benefiting competitors. With high competition, not only do incentives for basic research effort, which produces spillovers, decrease as spillovers become more pervasive. We show that it is optimal also to mute incentives for applied research effort, even if it does not generate spillovers. In turn, if knowledge spillovers are low or non-existent, firms provide the strongest incentives for basic and applied research both when they face very little competition and when competition is very high. In the former case, firms are bigger and cost reduction through R&D effort has a large impact on profits. In the latter case, cost reduction has a proportionally higher impact on profits, which are low due to the competitive pressure. Thus, the relationship between the intensity of competition and the power of incentives to scientists is U-shaped. In contrast, when there are high level of spillovers, the strength of incentives is decreasing in the intensity of competition.

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[2] Henderson and Cockburn (1994), Hicks (1995), Kinney et al. (2004), Stern (2004), Cockburn et al. (2006).

These two sets of results highlight the importance of the interactions between the conditions in the product market and in the transmission of knowledge, as key determinants of a company's R&D organization. Most of the existing empirical studies of the determinants of incentive schemes to corporate scientists abstract from these environmental conditions, potentially leading to biased estimates.

Finally, the third set of results concern the impact of a scientist's non-monetary motivation or taste for science from the performance of basic research on her pay scheme. Both the contingent part of the wage related to basic research effort, and the contingent part related to applied research, increase with non-pecuniary benefits scientists obtain from basic research. The response of scientists to steeper incentives is stronger when they also have intrinsic motives, leading to a large reduction in production costs, larger size and higher profits for the firm. Thus, companies optimally provide stronger incentives for basic research. In order to keep balance between the different tasks that scientists are called to perform, companies reinforce the incentives also for applied research, even if it does not produce non-monetary benefits to the scientists. A few studies argue that, since scientists care about their reputation through the performance of basic research companies might pay them lower wages if they allow the scientists to participate in the activities of their community of peer and possibly reward them also on the basis of their standing in the scientific community (Stern 2004, Aghion et al. 2005). However, it is not unheard of that some scientists receive very high pays for their services to companies, while at the same time enjoying autonomy and job satisfaction (Lee 2002). While complementarity between monetary incentives and non-monetary motives exists, we find 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 addition to interpreting the empirical evidence on the provision of incentives to corporate scientists, the model offers insights for the organization of R&D to entrepreneurs and managers. Our results stress the importance for firms to look at their position in the product market when designing their internal R&D organization. The model also informs on how to deal with researchers with different degrees of interest for monetary pay and for their reputation. Finally, considerations for a broader set of organizational issues and classes of workers can also be derived. For, other creative workers, such as in advertising or the arts in general, as well as in the health sector, may receive non-monetary benefits from some of their activities. From a public policy standpoint the results imply that, when competition in a given industry or submarket is low, a weak knowledge-appropriability regime may be optimal in order to stimulate the performance of basic research without excessively hurting firms' profits. Conversely, stronger IP protection may be required in order to stimulate innovation in more competitive environments. This complementarity between IP protection and antitrust laws is consistent with cross sectional evidence from several countries (Ganslandt 2008). Furthermore, policy makers should be aware that any interventions aimed at encouraging companies to stimulate one type of research will translate in companies designing incentive systems that balance different types of effort. The response to such policies will therefore be "softer than expected", if evaluated only in terms of one single dimension.

The model in this paper shares some similarities with previous theoretical works. Schmidt (1997), Raith (2003) and Vives (2004) analyze the provision of incentives to managers as they are affected by competition on the product market. Spence (1984), Qiu (1997), and Zhang and Zhang (1997) consider the presence of spillovers in R&D investments. Murdock (2002) considers a principal-agent model where agents also have intrinsic motivations. Our work builds on the insights of these studies, and extends on them by analyzing the impact of multidimensional effort, following the multitask agency theoretic approach pioneered by Holmstrom and Milgrom (1991, 1994). In addition to making the model more realistic for the analysis of incentive provision to scientists, the combination of these elements generates novel results and insight.[3]

The model is developed and solved in Section 1. The implications of the model, in terms of strength and complementarity of the incentive instruments under different environments, are analyzed in Section 2. Section 3 discusses the robustness of the model to alternative assumptions, and uses the model to interpret the existing empirical evidence on the determinants of incentive provision to scientists and to propose novel tests. Managerial and policy implications are also analyzed. A summary of the results and an outline of further avenues of research conclude the paper in Section 4. Appendix A summarizes the notation of the model. All of the proofs are in Appendix B.

1 The Model

1.1 Set up

The model is built as a four-stage game whose timing is represented in Figure 1 below.

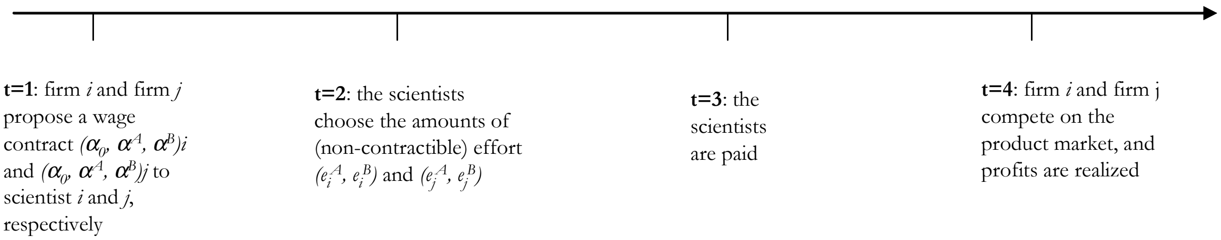

Figure 1: The game's timeline

A detailed description of the game's set up follows. Two firms, i and j, compete on the product market à la Cournot. The inverse demand function for firm i is given by:

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[3] Our study is also similar in spirit to Athey and Schmutzler (1995). Although in a different framework, these authors relate "shorter term" decisions, such as whether and how to exploit an innovation opportunities, to "longer term" organizational choices, such as the definition of incentive schemes to R&D workers.

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

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.[4] The total cost function for firm i is:

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

The marginal cost c_i is a function of the (unobservable, unverifiable) effort that a scientist, hired by the company's principal, exerts. 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 affects the marginal costs of firm i. Basic research activities by a company generate spillovers of knowledge to other companies, whose intensity depends on the size of the parameter β. Notice that β and λ are independent, i.e. 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. R&D activities aimed at a given product (or market segment) may indeed benefit firms in other segments. Finally, while different geographical areas may be isolated in terms of final product competitions (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. In this case, high product market competition may be accompanied by low knowledge spillovers.[5]

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". Effort costs are quadratic and separable. The utility function of a scientist hired by firm i has a negative exponential form:

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[4] 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: $U(q_1, q_2) = A(q_1 + q_2) - \frac{(q_i^2 + 2\lambda q_i q_j + q_j^2)}{2}$.

[5] 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). Bernstein and Nadiri (1988) and Rosenberg (1994) offer further examples of inter-industry knowledge spillovers. Alcacer and Zhao (2007) document that even firms located near each other that employ similar technologies may operate in different markets, and firms competing with each other may employ different technologies.

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

where r is the coefficient of absolute risk aversion, $\rho > 0$ is the degree of taste for science and $(\gamma^A, \gamma^B) \in \mathbb{R}^+ \text{ X } \mathbb{R}^+$ are parameters inversely related to the productivity of applied and basic research. We will generally assume $r > 0$, though will consider a few results also under risk neutrality.

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. In fact, there is evidence that firms base their performance pay on these measures (Henderson and Cockburn 1994, Cockburn et al. 2006).[6] Define:

$$\begin{aligned} X_i^A &= e_i^A + \varepsilon_i^A; \quad (5) \\ X_i^B &= e_i^B + \varepsilon_i^B, \quad (6) \end{aligned}$$

where $(\varepsilon_i^A, \varepsilon_i^B) \sim N(0, 0; \sigma_A^2, \sigma_B^2; \sigma_{AB})$. We assume that $\sigma_{AB} < \frac{1}{r}\frac{2(2-\lambda\beta)}{\gamma^A\gamma^B(\lambda+2)^2(2-\lambda)}$, i.e. that the correlation in the shocks on patent and paper production is not too high. This assumption, as we will see, is made to simplify the analysis. The wage schedule firm i proposes to scientist i takes a linear form:

$$w_i = \alpha_0 + \alpha^A X^A + \alpha^B X^B. \tag{7}$$

The variables α_0, α^A and α^B are under the control of the firm. The set up for firm j is fully symmetrical to that for firm i as just described.

Notice, finally, 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. 1996, Lacetera 2006). Knowledge spillovers, however, can still occur through more informal and less

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[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. 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 D'Amato et al. (2006). 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.

verifiable channels. These include interpersonal relations and conversations among scientists from different organizations, or 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 depending 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 benefit a rival firm, within the unit interval.

1.2 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.

1.2.1 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 first order condition for q_i gives the equilibrium quantity and profit:

$$\begin{aligned} q_i^* &= \frac{A - \frac{(2c_i - \lambda c_j)}{2-\lambda}}{\lambda + 2}; & (9) \\ \Pi_i^* &= [q_i^*]^2 = \left[\frac{A - \frac{(2c_i - \lambda c_j)}{2-\lambda}}{\lambda + 2}\right]^2. & (10) \end{aligned}$$

1.2.2 The scientist's effort choice

The effort choices of scientist i are straightforward to obtain, given the incentive scheme and the taste for science:

$$\begin{aligned} e_i^A &= \frac{\alpha_i^A}{\gamma^A}; & (11) \\ e_i^B &= \frac{\rho + \alpha_i^B}{\gamma^B}. & (12) \end{aligned}$$

1.2.3 The principal's problem

It is convenient to express the scientist's utility function in certainty equivalent terms. The principal's choice of the optimal contract is obtained from maximizing the expected total surplus TS, subject to the incentive compatibility constraints (11) and (12) (Holmstrom and Milgrom 1987). The program can be written as:

$$\begin{aligned} \underset{\alpha_0,\alpha^A,\alpha^B}{Max} E(TS_i) &= \Pi_i + \rho e_i^B - \frac{\left(e_i^A\right)^2}{2} - \frac{\left(e_i^B\right)^2}{2} - \\ & \frac{r}{2}\left[\left(\alpha_i^A\sigma_A\right)^2 + \left(\alpha_i^B\sigma_B\right)^2 + 2\alpha_i^A\alpha_i^B\sigma_{AB}\right] \end{aligned} \tag{13}$$

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

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

$$\begin{aligned} E(TS_i) &= \left[\frac{A}{\lambda+2} - \frac{2(c - \frac{\alpha_i^A}{\gamma^A} - \frac{\left(\rho+\alpha_i^B\right)}{\gamma^B} - \beta(\frac{\rho+\alpha_j^B}{\gamma^B})) - \lambda(c - \frac{\alpha_j^A}{\gamma^A} - \frac{(\rho+\alpha_j^B)}{\gamma^B} - \beta\frac{(\rho+\alpha_i^B)}{\gamma^B})}{(2-\lambda)(\lambda+2)}\right]^2 \\ & +\rho\frac{\left(\rho+\alpha_i^B\right)}{\gamma^B} - \frac{\left(\alpha_i^A\right)^2}{2\gamma^A} - \frac{\left(\rho+\alpha_i^B\right)^2}{2\gamma^B} - \frac{r}{2}\left[\left(\alpha_i^A\sigma_A\right)^2 + \left(\alpha_i^B\sigma_B\right)^2 + 2\alpha_i^A\alpha_i^B\sigma_{AB}\right]. \end{aligned} \tag{14}$$

Invoking symmetry – i.e. $\alpha_i^A = \alpha_j^A$ and $\alpha_i^B = \alpha_j^B$ – the first-order conditions become:

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

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

We assume that the second order conditions are satisfied.[7] Solving the system of the first order conditions and defining $k \equiv (\lambda+2)^2(2-\lambda)$, we obtain[8]:

$$\alpha_E^A = \frac{4k\left[\gamma^A\gamma^B(A-\overline{c})+\rho\gamma^A(1+\beta)\right]\left[4(1+r\gamma^B\sigma_B^2)-2(2-\lambda\beta)\gamma^A r\sigma_{AB}\right]}{\left\{\begin{array}{c}\left[\gamma^A k(1+r\gamma^A\sigma_A^2)-4\right]\left[\gamma^B k(1+r\gamma^B\sigma_B^2)-2(1+\beta)(2-\beta\lambda)\right] \\ -\left[4(1+\beta)-\gamma^A\gamma^B kr\sigma_{AB}\right]\left[2(2-\beta\lambda)-\gamma^A\gamma^B kr\sigma_{AB}\right]\end{array}\right\}}; \tag{17}$$

$$\alpha_E^B = \frac{4k\left[\gamma^A\gamma^B(A-\overline{c})+\gamma^B\rho(1+\beta)\right]\left[2(2-\lambda\beta)(1+r\gamma^A\sigma_A^2)-4\gamma^B r\sigma_{AB}\right]}{\left\{\begin{array}{c}\left[\gamma^A k(1+r\gamma^A\sigma_A^2)-4\right]\left[\gamma^B k(1+r\gamma^B\sigma_B^2)-2(1+\beta)(2-\beta\lambda)\right] \\ -\left[4(1+\beta)-\gamma^A\gamma^B kr\sigma_{AB}\right]\left[2(2-\beta\lambda)-\gamma^A\gamma^B kr\sigma_{AB}\right]\end{array}\right\}}. \tag{18}$$

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

[8] Under $\sigma_{AB} < \frac{1}{r}\frac{2(2-\lambda\beta)}{\gamma^A\gamma^B(\lambda+2)^2(2-\lambda)}$, α_E^A and α_E^B are positive when γ^A and γ^B are high enough.

The subscript E stands for "Equilibrium". Although expressions (17) and (18) do not appear to convey any immediate intuition, a series of comparative statics can be easily performed. These experiments are the subject of the following Section, where we study the impact of competition, knowledge spillovers and taste for science on the strength, direction and complementarity of incentive mechanisms.

2 Implications

The model generates results regarding the strength, direction, and relation among the incentive instruments a firm has under control in order to motivate scientists. The results are reported below in a series of propositions. We investigate three issues: i) the determinants of the relative strength of incentives; ii) comparative statics on the optimal incentive contract; and iii) the complementarity between the incentive instruments. The propositions are preceded by an informal description of, and the intuitions behind the results. The proofs of all of the propositions are in Appendix B.

2.1 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). Indeed, when $\beta = 0$ ($\lambda = 0$), the intensity of competition (the ease with which knowledge spills over to competitors) has no effect on the relative strength of incentives. The principal, moreover, provides higher powered incentives for the task which is more precisely observed. The firm, however, may still not provide full incentives for the more precisely measured activity, in order to avoid too much unbalance in the provision of the two types of effort. This derives from the assumption of risk aversion of the agent and of multi-task effort. As expected, the more applied research is productive, and the less basic research is, the stronger the incentives to perform applied research in relative terms. Finally, the ratio between the two piece rates turns out to be independent from the taste for science of the agent. The taste for science will be shown to affect, instead, the absolute value of the piece rates.

Proposition 1 *The ratio between the two piece rates,* $\frac{\alpha^A}{\alpha^B}$*, is i) increasing in* λ *and* β*; ii) increasing in* σ_B^2 *and* γ^B*; iii) decreasing in* σ_A^2 *and* γ^A*; iv) independent of* ρ*.*

2.2 The determinants of the optimal contract

2.2.1 Strength of incentives and knowledge spillovers

In general, the effect of knowledge spillovers (from basic research) on the absolute strength of incentives is ambiguous. On the one hand, there is positive effect of incoming spillovers: firms operate at lower costs and this leads firms to provide stronger incentives both for basic and applied research. On the other hand, giving strong incentives to scientists benefits the competing firms by reducing its costs though outgoing spillovers, thus increasing its size and profits at the detriment of the firm originating the spillovers. This has a negative effect on applied research as well, since firms need to balance the incentives for the two types of efforts. The overall impact of the degree of knowledge spillovers turns out to depend crucially in the intensity of product market competition.

Below, we will show a few numerical examples on the interaction between knowledge spillovers and competition in determining the optimal incentive contracts, for any possible level of competition and spillovers (the whole $[0,1]$ interval for both β and λ). Here, we begin with an analytical treatment of some limit cases, which offer most of the intuition on the working of the more general case. When firms are close to acting under a monopolistic situation, 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. This result shares the intuition of existing results with unidimensional effort (De Bondt 1997). The previous considerations are formalized in the following proposition:

Proposition 2 *If* $\lambda \to 0$, α_E^A *and* α_E^B *are both increasing in* β.

When considering the effect of knowledge spillovers (from basic research) on incentives for applied research (which does not spill over to competitors), both positive and negative forces are at work. First, there are the effects we mentioned: higher β means higher incoming spillovers (which positively affect α^A), but also higher outgoing spillovers (which negatively affects α^A by making the competitor tougher). In addition to these effects, there is a positive "substitution effect" that favors applied research against basic research, following from Proposition 1 above. This effect follows from assuming multidimensionality of effort and represents a contribution over similar models with one-dimensional effort, such ad De Bondt (1997). We show that the positive effect unambiguously dominate when the starting level of spillovers is low, as summarized in the following proposition:

Proposition 3 *If* $\beta \to 0$, α_E^A *is increasing in* β.

Our final proposition on the relationship between knowledge spillovers and the incentives piece rates concerns instead the effect of knowledge spillovers on the strength of incentives for basic research. When the product market is highly competitive and spillovers are high, the negative effect of outgoing spillovers is particularly strong. In this case, and if non-monetary benefits are sufficiently low, a further increase in β has an unambiguously negative effect o α^B.

Proposition 4 *If* $\lambda \to 1, \beta \to 1$ *and* $\rho \to 0$, α_E^B *is decreasing in* β.

2.2.2 Strength of incentives and intensity of competition

We now investigate the relationship between the strength of incentives provided to scientists and the intensity of competition as measured by λ. This issue is intimately related to 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 for deriving the relationship between product market competition and strength of incentives to scientific workers. We consider the special case of $\beta = 0$, i.e. full appropriability of basic research before moving to a more general treatment in the next section. In this special case, the shapes of $\frac{\partial \alpha_E^A}{\partial \lambda}$ and $\frac{\partial \alpha_E^B}{\partial \lambda}$ are similar. In particular, the relationship between the intensity of competition and the power of incentives to scientist is U-shaped, i.e. α_E^A and α_E^B are minimal for an intermediate level of λ.[9] There are two effects relating λ and the incentives to research. If λ is small, firms are larger, ceteris paribus. This provides high incentives for cost-reduction (such an effect can be seen in the denominator of (9), page 8). If λ is large, a firm's profits are more sensitive to its own costs (such an effect appears in the numerator of (9)). It turns out that the overall effect of competition on incentive strength is minimal for intermediate values of λ.[10]

Proposition 5 *If $\beta = 0$, α_E^A and α_E^B are decreasing in λ if $\lambda < \frac{2}{3}$, and increasing otherwise.*

2.2.3 Numerical examples

The high number of interacting effects makes the analysis of the general impact of β and λ on the absolute strength of incentives difficult. We studies analytically some special cases above. We now provide two numerical examples for the overall parameter space of β and λ. In the first example, we assume $r \to 0$, i.e. scientists are risk neutral. The other parameters are chosen in order to guarantee that second order conditions are satisfied for all values of β and λ.[11] Figure 2 shows three regions for the signs of $\frac{\partial \alpha_E^A}{\partial \beta}$ and $\frac{\partial \alpha_E^B}{\partial \beta}$. When the intensity of competition is sufficiently low, the positive effect of outgoing spillovers prevail, and both α_E^A and α_E^B are increasing in β (as shown by Proposition 2). 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. The negative effect of outgoing spillovers on incentives for basic research is particularly strong (see Proposition 4). Low investments in basic research lead firms to operate at higher costs, which is detrimental for the incentives to cost-reduction through applied research efforts. Finally, in the intermediate case the "substitution effect" mentioned above is at work, leading firms to

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[9] This result is similar to Belleflamme and Vergari (2006), where only one firm has the access to innovation, as in Arrow (1962). In their model, innovations are always perfectly appropriable. They do not consider how the results would change, in presence of knowledge spillovers.

[10] Whether the strength of incentives is highest in monopoly or in Cournot competition with homogenous products depends on the precision with which performances are measured.

[11] The examples are built using the following values: $A = 2$; $c = 1$, $\gamma_A = \gamma_B = 1.5$, $\rho = .2$. In the risk-neutrality cases, $r = 0$, and in the risk aversion examples, r is set equl to 2. Furthermore, in the risk aversion cases we have $\sigma_A^2 = \sigma_B^2 = 1.5$ and $\sigma_{AB} = 0.002$. Additional details on the construction of the examples are available from the authors.

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 (see Proposition 1). This leads to $\frac{\partial \alpha_E^A}{\partial \beta} > 0$ and $\frac{\partial \alpha_E^B}{\partial \beta} < 0$.

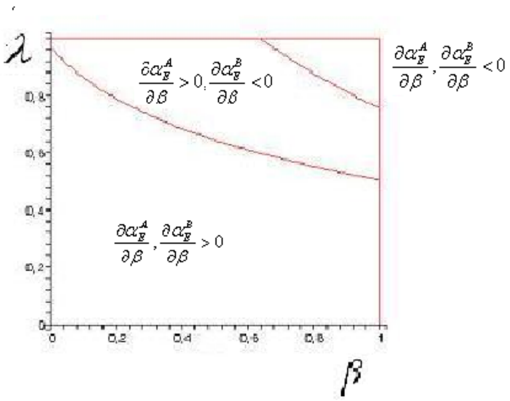

Figure 2: The impact of knowledge spillovers on the strength of incentives, for different combinations of knowledge spillovers and product market competition intensities, when scientists are risk neutral.

Figure 3 reports the marginal effect of λ on α_E^A and α_E^B. Both 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, in line with Proposition 5. 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.

In the second example we consider, we assume that the scientists are risk averse ($r = 2$). Regarding the marginal effect of β on α_E^A and α_E^B, only two relevant regions exist (Figure 4). In the first region, where the intensity of competition is low, α_E^A and α_E^B are increasing in β. If λ is sufficiently high, instead, we have $\frac{\partial \alpha_E^A}{\partial \beta} > 0$ and $\frac{\partial \alpha_E^B}{\partial \beta} < 0$. The intuition for this result is as follows. Assuming risk aversion instead of risk neutrality increases the cost of providing higher incentives for both applied and basic research. Then, the decreasing returns to R&D investments (which come from quadratic investment costs) are less severe, and this leads to favor the type of research investment which does not spill over to rivals. The same logic would apply following an increase of γ^A and γ^B (i.e. a reduction in the marginal product of effort) under risk neutrality.[12]

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[12] For instance, it can be shown that under the same parameterization of first example, except $\gamma^A = \gamma^B = 10$ and $\rho = 1$, no values of β and λ exist, for which both α_E^A and α_E^B are decreasing in λ.

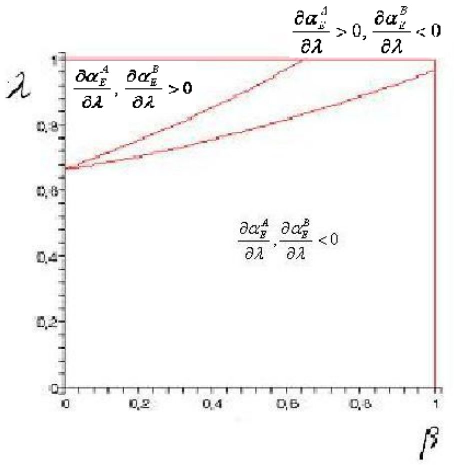

Figure 3: The impact of competitive pressure on the strength of incentives, for different combinations of knowledge spillovers and product market competition intensities, when scientists are risk neutral.

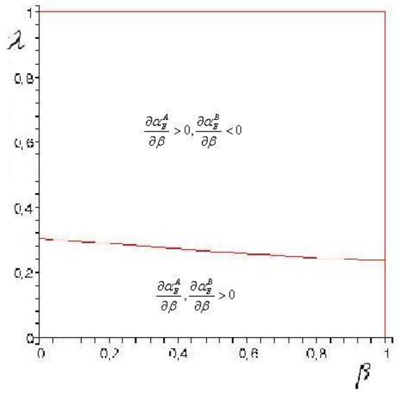

Figure 4: The impact of knowledge spillovers on the strength of incentives, for different combinations of knowledge spillovers and product market competition intensities, when scientists are risk averse.

Regarding the sign $\frac{\partial \alpha_E^A}{\partial \lambda}$ and $\frac{\partial \alpha_E^B}{\partial \lambda}$ under risk aversion (Figure 5), the picture is qualitatively similar to the case of risk neutrality. We can notice however, that for $\lambda > \frac{2}{3}$, the region in which both $\frac{\partial \alpha_E^A}{\partial \lambda}$ and $\frac{\partial \alpha_E^B}{\partial \lambda}$ are negative is smaller. This again is due to the operating of less severe decreasing returns in R&D investments.

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

An increase in the researcher's taste for science makes effort in basic research more attractive. This also makes the cost of providing higher-powered incentives for the performance of basic research effort less costly for the firm. For, the firm prefers to further reinforce these incentives through the wage schedule, in order to fully exploit the cost reduction effects of effort. The firm finds it optimal also to increase the power of the incentives on applied research, in order to keep balance between the two dimensions of effort. This result on the complementarity between extrinsic, monetary

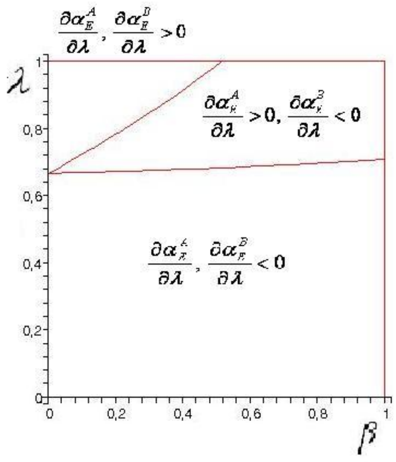

Figure 5: The impact of competitive pressure on the strength of incentives, for different combinations of knowledge spillovers and product market competition intensities, when scientists are risk neutral.

incentives and the intensity of intrinsic motives is similar to what Murdock (2002) finds. We add that, when effort is multidimensional, it is optimal for the principal to reinforce incentives both for the activities that generate non-monetary incentives for the agent, and for those that do not.

Proposition 6 α_E^A *and* α_E^B *are both increasing in* ρ*.*

Together with the investigation of the piece rates in the optimal contract, firms are also interested in determining the fixed component of wage. In the standard case, α_0 is simply determined by the participation constraint, which is binding in equilibrium. We are interested in determining how the fixed wage varies with ρ, the non-monetary benefit from basic research. The effect is a-priori ambiguous. Higher ρ implies that the scientist obtains a higher benefit from basic research. At the same time, as from Proposition 6, the scientist exerts higher effort in both applied and basic research, for which it must compensated. Under risk neutrality, it turns put the first effect prevail, and then α_0 is always decreasing in ρ. Under risk aversion, firms must compensate scientists for the risk they sustain. For this reason, it may be the case that α_0 is increasing in ρ. These results are summarized in the next proposition:

Proposition 7 *If* $r \to 0$, α_0 *is always decreasing in* ρ*. If* $r > 0$, α_0 *may be increasing in* ρ*.*

Finally, we look at the relationship between the overall expected wage $\alpha_0 + \alpha_E^A E(x_A) + \alpha_E^B E(x_A)$ and the degree of non-monetary benefits as expressed by ρ. We are able to partially characterize the case of risk neutrality. In particular, we can show that for low ρ the expected wage is increasing in ρ, i.e. that the effect on the piece rates prevails. For high ρ, we found examples both for the case in which the expected wage is increasing and for the case in which it is decreasing in ρ.

Proposition 8 *If* $r \to 0$, *the expected wage* $\alpha_0 + \alpha_E^A E(x_A) + \alpha_E^B E(x_A)$ *is increasing in* ρ *when* ρ *is small.* $\alpha_0 + \alpha_E^A E(x_A) + \alpha_E^B E(x_A)$ *may be increasing or decreasing in* ρ *when* ρ *is high.*

2.3 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 most profitable choice of each single effort-enhancing measure (Holmstrom and Milgrom 1994, Cockburn et al. 2006). In addition to considering the impact of the model parameters on the incentive measures separately, the model also holds predictions on how the piece rates co-move, following changes in the parameters of the model. Some of the complementarity results that follow can be derived from the analysis in the previous section. However, a separate and complete analysis is proposed here, using supermodularity techniques. Notice that a necessary condition for complementarity is that $\frac{\partial^2 E(TS)}{\partial \alpha_i^A \partial \alpha_i^B} \geq 0$, that holds whenever $\sigma_{AB} < \frac{1}{r} \frac{2(2-\lambda\beta)}{\gamma^A \gamma^B (\lambda+2)^2 (2-\lambda)}$ is true, as we assumed. It will be shown, again, that the environmental conditions, and the interactions among them, are crucial in order to determine whether the available incentive instruments move in the same direction or not.

2.3.1 Complementarity between α_i^A and α_i^B, and changes in 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. This result generalize the numerical examples we provide, with the same logic.

Proposition 9 α_i^A *and* α_i^B *are complementary in* λ *for every* γ^A *and* γ^B *if* $\lambda > \overline{\lambda}(\beta)$, *with* $\overline{\lambda}(\beta) \geq \frac{2}{3}$ *and* $\overline{\lambda}'(\beta) > 0$.

2.3.2 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 2).

Proposition 10 α_i^A *and* α_i^B *are complementary in* β *if* λ *is small.*

2.3.3 Complementarity among α_i^A and α_i^B, and researchers' taste for science

The following result is equivalent to the finding formalized in Proposition 6 (page 15).

Proposition 11 α_i^A,α_i^B *and* ρ *are always complementary.*

3 Discussion

In this section, we first discuss the robustness of the model's results to alternative assumptions. Second, we argue, through the analysis of three prominent empirical papers, that the model provides a novel interpretation to some R&D organizational choices of companies. A series of empirical tests motivated by the model are also proposed. We then explore the managerial and public policy implications of the findings.

3.1 Robustness

Our results have been obtained under some specific assumptions, which naturally leads to the question of their robustness. A few assumptions have been motivated when setting up the model in Section 1. A few additional assumptions are discussed here. First, we consider only the case of Cournot competition (with linear inverse demand). Other forms of competition, notably Bertrand, could have been used. In the case of unidimensional effort, Cournot competition is more conducive to cost-reducing R&D than Bertrand, ceteris paribus, because of the strategic effect (Qiu, 1997). With Cournot competition, higher investment in R&D makes the firm tougher in the market and this discourages its rival's sales, which guarantees further benefits. In the Bertrand case, the firm's R&D lowers its cost and induces its rival to cut its price, which is detrimental to both. While the form of competition affects the *level* of the piece rates, the effect of intensity of competition and knowledge spillovers depends on the cross-derivative of profits with respect to applied and basic research being positive (which would hold also under Bertrand competition), and the degree of spillovers of basic research being higher than the one for applied research. Incidentally, this last point implies that our results would be qualitatively unchanged (although less strong) if spillovers were strictly positive also for applied research – therefore, not only is the assumption of quantity competition not particularly restrictive, but also the assumption of spillovers coming only from basic research can be relaxed.

Second, in the model the research effort is taken as generating process innovations, i.e. as reducing production costs. The framework, however, can accommodate product innovation in a natural fashion. Product innovation 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 equation (1). The firms' profit functions, and therefore their optimal decisions, will be unaffected as compared to the case above (see Vives 2006 for a similar argument).

Regarding the result on complementarities between monetary and non monetary incentives, this hinges on the positive sign of the cross-derivative of profits with respect to applied and basic research and on the "taste for science" being expressed as positive component in scientist's utility function; for instance, complementarity could fail if it were captured by a lower cost parameter in the investment function. What is crucial is that scientists would exert basic research effort even in absence of any monetary incentives for basic research, and that applied and basic research are complementary in the profit function.

Another assumption we made is that applied and basic research efforts enter linearly into the cost function. An alternative way would have been to assume (also) an interactive effect between the two; in particular, the basic research could increase the marginal return from applied research (possibly without a direct effect). This assumption would add another source of complementarity between applied and basic research, increasing the likelihood of co-movements of the piece rates. Finally, the specific form of the utility function, while being convenient for tractability, has no impact on the results. In particular, higher risk aversion is always substantially equivalent to higher cost for performing R&D.

3.2 Interpretation of the empirical evidence, and proposals for additional tests

Stern (2004) 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. Under risk-neutrality, 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 science-oriented researcher to give up money in exchange for science, act 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, and low risk aversion, our results directly points at his work.[13]

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. Furthermore, two key variables appear as omitted in Stern's study: the competitive conditions in which the firms operate, and the degree to which research results are expected to spill over to competitors. Empirical controls for the characteristics of the final markets, and of the technologies in which the different employers are engaged, are therefore warranted.

Cockburn et al. (2006) Cockburn et al. (2006) study the relation between the provision, by large pharmaceutical companies, of incentives for basic and applied research to their scientists.

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

They find evidence for complementarity between these two classes of incentives: 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 do not account for the possibility that complementarity depends on the competitive environment and the degree of IP protection. In fact, the theoretical analysis that precedes the empirical part of the paper implicitly assumes a monopolistic firm. Competitive pressure, and its interaction with the extent of knowledge spillovers, may play a major role in the incentive design, however. Cockburn et al. employ data at the level of the single research program, and control for research program as well as firm fixed effects in their regressions. Arguably, different research programs refer to different final product markets, with potentially different competitive and spillovers conditions. An extension of the work of Cockburn et al. would be to calculate the relation between basic and applied research incentives separately for each submarket, and compare the sign and magnitude of the estimated parameters across these different markets.

Andersson et al. (2006) Andersson et al. (2006) analyze the wage structures of software developers in firms. They 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 environment 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. First, software developers may derive also 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. Second, a more "risky" industry segment might also be a more concentrated one. For example, the video game software developing/publishing segment, indicated by Anderrson 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, Anderrson et al. indicate "networking" as the riskiest, and "database" as the least risky. In addition, intellectual property protection in software relatively weak, and knowledge spillovers are pervasive.[14] If higher riskiness goes together with higher concentration, and intel-

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[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 in software 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 even patents

lectual property protection is weak, then our model predicts that companies offer higher powered incentives in less competitive product lines. This explanation adds to the one offered by Anderrson et al. in terms of sorting of higher skilled workers into higher risk companies.

3.3 Managerial and public policy implications

3.3.1 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 some market power, cost-reducing efforts by its scientists are likely to have a sizeable impact on the absolute 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 from a world of more "private" knowledge. Conversely, knowledge spillovers have a very different nature in highly and weakly competitive markets. In the former, as said, they offer an advantage to competitors which, in turn backfires on the focal company. When competition on the product market is low, by 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. A part of business strategy in knowledge-driven industries would therefore be to figure out whether, in a particular market, the level of competition and the degree of knowledge spillovers are related or not.

Finally, scientists who are more eager to maintain their links to the scientific community even when employed by a firm, and allowed by a firm to do so, are not necessarily "cheap". Instead, these are the scientists that will need to be given more powerful incentives for the performance of both basic and applied research.

The analysis can be applied to how companies 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 includes such industries as health care and advertising (Gaynor et al. 2005, Von Nordenflycht 2007), and such organizations

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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 this ideas. The phenomenon is particularly strong in the software industry, due to the fact that a large share of firms is clustered in a relatively small geographical area (Freedman 2006).

as universities, hospitals, and the military.

3.3.2 Public policy insights

Both the scholarly and popular press have documented a decline, in more recent years, of public funds for basic research, even to those agencies, such as the NIH, which had enjoyed an upsurge of funding in previous periods (Bridges 2006). Especially in times of tighter public budget constraints, companies might be called for having a more active and extensive role in the performance of basic research. Should we expect companies to fulfill this expectation? Considerations on the interaction between competitive and appropriability conditions, and the multitask nature of research activities, can offer insights to answer this question. In industries where competition is low, say because companies operate in relatively separated submarkets, promoting higher knowledge spillovers through weaker intellectual property right may lead companies to offer stronger incentives to their scientists also for the performance of basic, open science. We have shown that, 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 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 complementarity between patent protection and antitrust laws. Ganslandt (2008) shows, in fact, that there is a strong, positive correlation, across countries, between strength of IP protection and effectiveness of antitrust regulations.

In a multitask setting like the one modeled in this paper, finally, policy makers need also to acknowledge that any policy aimed at promoting basic research activities by firms might see a "softer" response by company than expected. When scientific workers perform multiple productive activities, companies devise their incentive schemes in order for the overall incentive system to be in balance. Therefore, in response to policies that facilitate the performance of basic research, companies might change their incentive structure in order to strengthened incentives for the performance of basic research, but not to a full extent, in order not to excessively deviate researchers' activities from other productive tasks.

4 Summary and directions for further research

The model of incentive provision to company scientists developed in this paper is based on four key claims and assumptions. First, scientist engage in multiple, different activities when performing research, e.g. (proprietary) applied and (open) basic research. Second, the immediate outcome of research activities, knowledge, is only imperfectly appropriable. Third, while scientists are responsive to the provision of monetary incentives, they also care about less material outcomes, such as their reputation and recognition in their broader community of peers. Fourth, the provision of incentives to scientists, and all workers in general, depends on the conditions a firm faces in the product market, such as the type and intensity of competition. The simultaneous considerations of these issues in a single model is novel, and allows for a more realistic representation of R&D incentive problems, as well as for elaborating novel predictions and implications. We find that the relative strength of incentives for applied 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 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. An additional, important results is that both the incentives for applied and basic research increases with non-pecuniary benefits 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 have implication for the interpretation of the existing empirical evidence on the provision of incentives to knowledge workers, and also suggest additional test to be performed. The previous section has discussed these implication, as well as the insights that the model generates for managers and policy makers. The robustness and the limits of the model with respect to a number of alternative assumptions have also been already addressed in the paper. Here we suggest a few avenues for further theoretical analyses. First, a richer set up would consider firms as differing in their focus on or their efficiency in different types of research, as well as scientists differing in their abilities and tastes for science. A further extension, related to the one just described, would be to consider also the interaction between the incentive provision problem and the labor market for scientists. The incentives schemes would be devised also in order to equalize returns across firms, and if firms and scientists are heterogeneous, matching dynamics would also be relevant to account for. The model, finally, is developed from the firms' standpoints, and focuses on competition among firms. Further development would explore also how the incentive provision problem change, when firms formally cooperate with each other in R&D.[15] 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.

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A Notation

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_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 salary
ρ	Scientists' non monetary benefits per unit of basic research effort
$X_i^A,\ X_i^B$	Performance measures for applied and basic effort, respectively, used by the firms to determine the scientists' wage
$\sigma_A^2,\ \sigma_B^2,\ \sigma_{AB}$	Variances of the error components of X_i^A and X_i^B respectively, and their covariance
c_i	Marginal cost of production
c	Fixed component of the marginal cost function
$\beta \in [0,1]$	Degree with which scientist j's the 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

B Proofs

Proof of Proposition 1 The ratio $\frac{\alpha_E^A}{\alpha_E^B}$ is equal to

$$\frac{\alpha_E^A}{\alpha_E^B} = \frac{4(1+r\gamma_B\sigma_B^2)-2(2-\lambda\beta)r\gamma_A\sigma_{AB}}{2(2-\lambda\beta)(1+r\gamma_A\sigma_A^2)-4r\gamma_B\sigma_{AB}} \tag{19}$$

ρ does not appear in $\frac{\alpha_E^A}{\alpha_E^B}$. The claims for λ, β are immediate, since the numerator in increasing in these parameters, while the denominator is decreasing. σ_A^2 appears only in the denominator, which is increasing in this parameter, while σ_B^2 appears only in the numerator, which is also increasing in the parameter. Finally, the numerator is increasing in γ_B while the denominator is decreasing in this parameter. The opposite is true for γ_A.

Proof of Proposition 2 We first compute $\frac{\partial\alpha_E^A}{\partial\beta}$ and $\frac{\partial\alpha_E^A}{\partial\beta}$:

$$\frac{\partial\alpha_E^A}{\partial\beta} = \frac{\begin{array}{c} \left\{ \begin{array}{c} \gamma_A\rho k\left[4(1+r\gamma_B\sigma_B^2){-}2(2-\lambda\beta)r\gamma_A\sigma_{AB}\right] \\ +\left[\gamma^A\gamma^B(A{-}\overline{c}){+}\rho\gamma^A(1+\beta)\right]k2\lambda rr\gamma_A\sigma_{AB} \end{array} \right\}\Delta- \\ k\left[\gamma^A\gamma^B(A{-}\overline{c}){+}\rho\gamma^A(1+\beta)\right]\left[4(1+r\gamma^B\sigma_B^2)-2\left(2-\lambda\beta\right)\gamma^A r\sigma_{AB}\right]* \\ \left\{ \begin{array}{c} -2\left[\gamma^A k(1+r\gamma^A\sigma_A^2)-4\right](2-2\lambda\beta-\lambda) \\ -4\left[2(2-\beta\lambda){-}\gamma^A\gamma^B kr\sigma_{AB}\right]+2\lambda\left[4(1+\beta){-}\gamma^A\gamma^B kr\sigma_{AB}\right] \end{array} \right\} \end{array}}{\Delta^2} \tag{20}$$

$$\frac{\partial\alpha_E^B}{\partial\beta} = \frac{\begin{array}{c} \left\{ \begin{array}{c} \gamma_A\rho k\left[2(2-\lambda\beta)(1+r\gamma_A\sigma_B^2){-}4r\gamma_B\sigma_{AB}\right] \\ -\left[\gamma^A\gamma^B(A{-}\overline{c}){+}\rho\gamma^A(1+\beta)\right]k2\lambda(1+r\gamma_A\sigma_B^2) \end{array} \right\}\Delta \\ -k\left[\gamma^A\gamma^B(A{-}\overline{c}){+}\rho\gamma^A(1+\beta)\right]\left[2(2-\lambda\beta)(1+r\gamma_A\sigma_B^2){-}4r\gamma_B\sigma_{AB}\right]* \\ \left\{ \begin{array}{c} -2\left[\gamma^A k(1+r\gamma^A\sigma_A^2)-4\right](2-2\lambda\beta-\lambda) \\ -4\left[2(2-\beta\lambda){-}\gamma^A\gamma^B kr\sigma_{AB}\right]+2\lambda\left[4(1+\beta){-}\gamma^A\gamma^B kr\sigma_{AB}\right] \end{array} \right\} \end{array}}{\Delta^2} \tag{21}$$

where $\Delta = \left[\gamma^A k(1+r\gamma^A\sigma_A^2)-4\right]*\left[\gamma^B k(1+r\gamma^B\sigma_B^2)-2(1+\beta)(2-\beta\lambda)\right]-\left[4(1+\beta){-}\gamma^A\gamma^B kr\sigma_{AB}\right]$ $*\ \left[2(2-\beta\lambda){-}\gamma^A\gamma^B kr\sigma_{AB}-\right]$. $\frac{\partial\alpha_E^A}{\partial\beta}$ is the difference of two quantities. The first one is always positive, while the second one is itself the product of two quantities: the first one is always positive (being the numerator of α_E^A), the second one ($\frac{\partial\Delta}{\partial\beta}$) has an ambiguous sign. When $\lambda \to 0$, we have:

$$\frac{\partial\Delta}{\partial\beta}{=}\left\{-4\left[\gamma^A k(1+r\gamma^A\sigma_A^2)-4\right]-4\left[4{-}\gamma^A\gamma^B kr\sigma_{AB}\right]\right\}<0,$$

since $\gamma^A k(1+r\gamma^A\sigma_A^2)-4$ from the second order conditions and $4-\gamma^A\gamma^B kr\sigma_{AB} > 0$ is implied by $\sigma_{AB} < \frac{1}{r}\frac{2(2-\lambda\beta)}{\gamma^A\gamma^B(\lambda+2)^2(2-\lambda)}$.Then, overall, we have $\frac{\partial\alpha_E^A}{\partial\beta} > 0$. Also $\frac{\partial\alpha_E^B}{\partial\beta}$ is the difference of two quantities. When $\lambda \to 0$, the first quantity is positive. The second one is the product of the numerator of α_E^B, which is always positive, and $\frac{\partial\Delta}{\partial\beta}$, which is negative as we have just shown. Then, overall, we have $\frac{\partial\alpha_E^B}{\partial\beta} > 0$.

Proof of Proposition 3 When $\beta \to 0$, we have:

$$\frac{\partial\Delta}{\partial\beta} = \left\{-2(2-\lambda)\left[\gamma^A k(1+r\gamma^A\sigma_A^2)-4\right]-(4-2\lambda)\left[4{-}\gamma^A\gamma^B kr\sigma_{AB}\right]\right\}<0. \tag{22}$$

As shown in the previous proof, this implies $\frac{\partial\alpha_E^A}{\partial\beta} > 0$.

Proof of Proposition 4 Consider $\frac{\partial\alpha_E^B}{\partial\beta}$ when $\beta \to 1$, $\lambda \to 1$ and $\rho \to 0$. The first quantity is negative, since it is the product of $-\left[\gamma^A\gamma^B(A{-}\overline{c})\right]18r\gamma_A\sigma_{AB} < 0$ and $\Delta > 0$. The second quantity is the product of the numerator of α_E^B, which is positive, and $\frac{\partial\Delta}{\partial\beta}$, for which we have:

$$\begin{aligned} \frac{\partial\Delta}{\partial\beta} &= \left\{2\left[\gamma^A k(1+r\gamma^A\sigma_A^2)-4\right]-4\left[2{-}\gamma^A\gamma^B kr\sigma_{AB}\right]+2\left[2{-}\gamma^A\gamma^B kr\sigma_{AB}\right]\right\} \\ &= \left\{2\left[\gamma^A k(1+r\gamma^A\sigma_A^2)-4\right]+8+2\gamma^A\gamma^B kr\sigma_{AB}\right\}>0. \end{aligned} \tag{23}$$

Proof of Proposition 5 If $\beta = 0$, we have:

$$\alpha_E^A = \frac{4k\left[\gamma^A\gamma^B(A-\overline{c})+\rho\gamma^A\right]\left[4(1+r\gamma^B\sigma_B^2)-4\gamma^A r\sigma_{AB}\right]}{\left[\gamma^A k(1+r\gamma^A\sigma_A^2)-4\right]\left[\gamma^B k(1+r\gamma^B\sigma_B^2)-4\right]-\left[4-\gamma^A\gamma^B kr\sigma_{AB}\right]^2}; \tag{24}$$

$$\alpha_E^B = \frac{4k\left[\gamma^A\gamma^B(A-\overline{c})+\gamma^B\rho\right]\left[4(1+r\gamma^A\sigma_A^2)-4\gamma^B r\sigma_{AB}\right]}{\left[\gamma^A k(1+r\gamma^A\sigma_A^2)-4\right]\left[\gamma^B k(1+r\gamma^B\sigma_B^2)-4\right]-\left[4-\gamma^A\gamma^B kr\sigma_{AB}\right]^2}. \tag{25}$$

Computing $\frac{\partial \alpha_E^A}{\partial k}$, we obtain:

$$\frac{\partial \alpha_E^A}{\partial k} = \frac{4\left[\gamma^A\gamma^B(A-\overline{c})+\rho\gamma^A\right]\left\{\begin{array}{c}\Delta - k\left[\gamma^A k(1+r\gamma^A\sigma_A^2)-4\right]\gamma^B(1+r\gamma^B\sigma_B^2)+\\ \gamma^A k(1+r\gamma^A\sigma_A^2)\left[\gamma^B k(1+r\gamma^B\sigma_B^2)-4\right]\\ +2\gamma^A\gamma^B r\sigma_{AB}\left[4-\gamma^A\gamma^B kr\sigma_{AB}\right]\end{array}\right\}}{\Delta^2} \tag{26}$$

which has the same sign as:

$$-k^2\gamma^A\gamma^B\left[(1+r\gamma^A\sigma_A^2)^B(1+r\gamma^B\sigma_B^2)-r^2(\sigma_{AB})^2\gamma^A\gamma^B\right]. \tag{27}$$

This quantity is negative since $\sigma_{AB} < \sigma_A\sigma_B$. Thus, α_E^A is decreasing in k. Since $\frac{dk}{d\lambda} = 2(2+\lambda)(2-3\lambda)$, k is increasing in λ when $\lambda < \frac{2}{3}$, and decreasing otherwise. This implies that α_E^A is decreasing in λ when $\lambda < \frac{2}{3}$, and increasing for $\lambda > \frac{2}{3}$.

Proof of Proposition 7 In equilibrium, the agent's participation constraint will bind:

$$\begin{aligned} E(U_i) \quad = \quad & \alpha_0 + \alpha_E^A\left(\frac{\alpha_E^A}{\gamma^A}\right) + \alpha_E^B\left(\frac{\alpha_E^B+\rho}{\gamma^B}\right) + \rho\left(\frac{\alpha_E^B+\rho}{\gamma^B}\right) - \\ & \frac{\gamma^A\left(\frac{\alpha_E^A}{\gamma^A}\right)^2}{2} - \frac{\gamma^B\left(\frac{\alpha_E^B+\rho}{\gamma^B}\right)^2}{2} - \frac{r}{2}\left[\left(\alpha_E^A\sigma_A\right)^2 + \left(\alpha_E^B\sigma_B\right)^2 + 2\alpha_E^A\alpha_E^B\sigma_{AB}\right] = \overline{u}, \end{aligned} \tag{28}$$

where the equilibrium values for efforts are substituted into the expression. $\overline{u}$ is the reservation utility for the scientist. Simplifying the expression, we are left with:

$$E(U_i) = \alpha_0 + \frac{\left(\alpha_E^A\right)^2}{2\gamma^A}(1-r\sigma_A^2) + \frac{\left(\alpha_E^B\right)^2}{2\gamma^B}(1-r\sigma_B^2) - r\alpha_E^A\alpha_E^B\sigma_{AB} + \frac{\rho^2}{2\gamma^B} + \frac{\rho\alpha_E^B}{\gamma^B} \tag{29}$$

For $r \longrightarrow 0$, at the limit the previous expression reduces to

$$E(U_i) = \alpha_0 + \frac{\left(\alpha_E^A\right)^2}{2\gamma^A} + \frac{\left(\alpha_E^B\right)^2}{2\gamma^B} + \frac{\rho^2}{2\gamma^B} + \frac{\rho\alpha_E^B}{\gamma^B}. \tag{30}$$

The quantity $\frac{\left(\alpha_E^A\right)^2}{2\gamma^A} + \frac{\left(\alpha_E^B\right)^2}{2\gamma^B} + \frac{\rho^2}{2\gamma^B} + \frac{\rho\alpha_E^B}{\gamma^B}$ is increasing in ρ since all its terms are increasing in ρ. As a consequence, α_0, the fixed component of wage, is decreasing in ρ in order for $E(U_i)$ to be constant. A numerical example in which α_0 is increasing in ρ at least for some values of ρ is $r = 5$, $A = 2$, $c = 1$, $\lambda = \beta = 0.5$, $\sigma_A^2 = \sigma_B^2 = 1$, $\sigma_{AB} = 0.01$, $\gamma^A = \gamma^B = 1$. Under this parameterization, we obtain $\frac{\partial \alpha_0}{\partial \rho} = 0.002519 - 1.1067\rho$, which is positive when ρ is sufficiently low ($\rho < 0.0022$).

Proof of Proposition 6 Immediate by inspection of expressions (17) and (18), since ρ appears only in the two numerators, which are both increasing in ρ.

Proof of Proposition 8 If $r \to 0$, then $E(w) = \overline{u} + \frac{\left(\alpha_E^A\right)^2}{2\gamma^A} + \frac{\left(\alpha_E^B\right)^2}{2\gamma^B} - \frac{\rho^2}{2\gamma^B}$. Differentiating with respect to ρ, we obtain $\frac{\partial E(w)}{\partial \rho} = \gamma_B(1+\beta)\alpha_A + \gamma_A(1+\beta)\alpha_B - \rho$, which is positive for $\rho \to 0$. An example for which $\frac{\partial E(w)}{\partial \rho}$ is always increasing in ρ is $A = 2$, $c = 1$, $\lambda = 1$, $\beta = 0.5$, $\gamma^A = \gamma^B = 1.5$, 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 $A = 2$, $c = 1$, $\lambda = 0.2, \beta = 0.5, \gamma^A = \gamma^B = 5$, from which we get $\frac{\partial E(w)}{\partial \rho} = 0.0398 - 0.1880\rho$.

Proof of Proposition 9 If we compute the cross-derivatives with respect to λ, we obtain:

$$\frac{\partial^2 E(TS)}{\partial \alpha_i^A \partial \lambda} = \frac{\partial q_i}{\partial \lambda} \frac{4}{\gamma^A(\lambda+2)(\lambda-2)} + \frac{q_i}{\gamma^A} \frac{8\lambda}{(4-\lambda^2)^2} > 0 \tag{31}$$

$$\frac{\partial^2 E(TS)}{\partial \alpha_i^B \partial \lambda} = \frac{\partial q_i}{\partial \lambda} \frac{4}{\gamma^B(\lambda+2)(\lambda-2)} + \frac{q_i}{\gamma^B} \left[\frac{8(\lambda-\beta)}{(4-\lambda^2)^2}\right] > 0 \tag{32}$$

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 $\lim\limits_{\substack{\gamma^A \to \infty \\ \gamma^B \to \infty}} q_i = \frac{(A-c)}{(\lambda+2)}$.

Then, supermodularity holds for all γ^A and γ^B if

$$2\lambda > (2-\lambda) \tag{33}$$

$$4(\lambda-\beta) > (2-\beta\lambda)(2-\lambda) \tag{34}$$

The first inequality is satisfied if $\lambda > \frac{2}{3}$. As the second inequality is concerned, we define $H(\lambda,\beta) = 4(\lambda-\beta) - (2-\beta\lambda)(2-\lambda)$. We have:

$$\frac{\partial H(\beta,\lambda)}{\partial \lambda} = 4 + \beta(2-\lambda) + (2-\beta\lambda) > 0; \tag{35}$$

$$H(\lambda,\beta)|_{\beta=0} = 6\lambda - 4; \tag{36}$$

$$\frac{\partial \lambda}{\partial \beta} = \frac{8 - 4\lambda + 4\beta\lambda}{12 + 4\beta - 4\beta\lambda} > 0, \tag{37}$$

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

Proof of Proposition 10 From (15) and (16), respectively, we obtain, after invoking symmetry:

$$\frac{\partial^2 E(TS)}{\partial \alpha_i^A \partial \beta} = \tfrac{(\alpha_i^B+\rho)}{k}\frac{4}{\gamma^A} \geq 0 \tag{38}$$

$$\frac{\partial^2 E(TS)}{\partial \alpha_i^B \partial \beta} = \tfrac{(\alpha_i^B+\rho)}{k}\left[\tfrac{2(2-\beta\lambda)}{\gamma^B}\right] - q_i\left[\tfrac{2\lambda}{\gamma^B(2-\lambda)(2+\lambda)}\right]. \tag{39}$$

For $\lambda \rightarrow 0$, (39) is positive, so that we have the claim

Proof of Proposition 11 The proposition derives from Proposition 6 (page 15). We can also see that:

$$\frac{\partial E(TS)}{\partial \alpha_i^A \partial \rho} = 2\left[\tfrac{1+\beta}{\gamma^B(2+\lambda)}\right]\left[\tfrac{2}{\gamma^A(2-\lambda)(2+\lambda)}\right] > 0; \tag{40}$$

$$\frac{\partial E(TS)}{\partial \alpha_i^B \partial \rho} = 2\left[\tfrac{1+\beta}{\gamma^B(2+\lambda)}\right]\left[\tfrac{2-\beta\lambda}{\gamma^B(2-\lambda)(2+\lambda)}\right] > 0. \tag{41}$$