Banal-Estanol, A. & Macho-Stadler, I. (2010). Scientific and Commercial Incentives in R&D: Research versus Development?. Journal of Economics and Management Strategy, 19(1), pp. 185-221. doi: 10.1111/j.1530-9134.2009.00250.x

Scientific and Commercial Incentives in R&D: Research versus Development?*

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April 27, 2009

Abstract

This paper proposes a framework to analyse the effects of scientific and commercial incentives in R&D organisations. We build a simple repeated model of a researcher capable of obtaining innovative ideas. Although they reduce the time spent on research, we show that commercialisation incentives also affect the choice of research projects. Commercial rewards induce a more intensive search for (ex-post) path-breaking innovations, which are more likely to be generated through (ex-ante) riskier research programs. We derive the organisation's optimal incentive scheme in terms of the researcher's characteristics. We show that organisations should use a high level of commercial incentives for scientists who have strong or weak intrinsic preferences for research. For those with strong preferences, the organisation needs to induce development, while for those with weak ones, it needs to induce effort.

*An earlier version of this paper was circulated under the title "Commercial Incentives in Academia". We are grateful to David Pérez-Castrillo, Reinhilde Veugelers, the coeditor and two referees for valuable discussions and helpful comments. We have also benefitted from the comments of seminar participants at the Universities Autonoma de Barcelona, Padova and Porto and at the JEI (Barcelona, 2006) EEA (Budapest, 2007), ASSET (Florencia, 2008). Financial support from Ministerio de Ciencia y Tecnología (SEJ2006-00538), Consolider-Ingenio 2010 (CSD 2006-00016), Barcelona GSE Research Network and from the Government of Catalonia (2005SGR00836) is gratefully acknowledged.

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1 Introduction

The success of R&D organisations depends, as their name indicates, on *both* research *and* development. The long-run profits of pharmaceutical firms, for instance, depend, not only on the successful development of potentially marketable drugs, but also on the ability to understand and solve fundamental scientific problems (Cockburn et al., 1999b). Although investments in pure research might not have an immediate payoff, they contribute to the firms' long-run capabilities and to their "absorptive capacity" (Cohen and Levinthal, 1989 and Gambardella, 1992). Novartis, for example, states that "the breadth of science we encompass is tremendous, embracing the entire spectrum from fundamental to clinical investigation". Drug companies such as Novartis, Merck and AstraZeneca have been aggressively recruiting researchers from academic centres. But it is not only drug companies that recruit researchers with a "taste" for science (Stern, 2004). IBM Research hires PhD and post-doc researchers in nanotechnology and computational biology; Microsoft hires mathematicians in order "to pursue outstanding questions in computer sciences".

Similarly, the ability of universities and other public research institutions to attract funds no longer depends exclusively on research performance. Funds stemming from patents, licences and contract research are needed to compensate for the declining share of government funding (Mansfield, 1995). As argued by Etzkowitz (2003), research universities around the world are becoming "quasi-firms", in the sense that they are increasingly encouraged to develop and sell their knowledge and technology.

Thus, managers in all R&D organisations (both firms and universities) need to balance incentives for obtaining scientific results with incentives for producing patents and licences. This paper spells out, in a first step, the effects of commercial and research rewards on the allocation of time between research on the one hand, and development on the other. We investigate, in a second step, how the introduction of commercial rewards affects the choice of research projects. We analyse, in particular, the concerns of various commentators who claim that the introduction of commercial rewards in academia might be "skewing" research, from basic towards more applied research projects (Florida and Cohen, 1999). In a third step, we design the optimal incentive scheme taking into account the organisation's objectives and the employee's characteristics.

Indeed, research organisations differ, to a great extent, as to what importance they attach to scientific results versus commercial value. Research intensive companies, for example, are more likely to prioritise commercial value than universities or other public research institutions. But there might also be differences across universities and across firms. Following the Bayh-Dole Act, some universities, such as Iowa University, have included technology licensing and commercial arrangements in their strategic plans, while others have not. Cockburn et al. (1999a) identify and measure varying intensities of research incentives in drug companies, using the importance given to the standing in the research community as a factor for promotion and other rewards.[1]

R&D contracts also need to take into account the preferences of the recruited scientists. As argued by Stern (2004), scientists are a special type of employee. First, researchers are not only driven by promotion and monetary rewards but also by peer recognition and the "puzzle" joy (Stephan and Levin, 1992). Researchers might have an intrinsic preference for research, besides the explicit incentives provided by the organisation. Second, scientists value (and are offered) substantial discretion in the choice of research projects.

This paper proposes a framework to analyse the effects of scientific and commercial incentives on the pattern of research. We build a simple repeated model of a researcher capable of obtaining innovative ideas. In each period, the researcher might decide to undertake new research, thus generating a new idea. In our basic model, each idea has both scientific and potential commercial value, in line with recent evidence that shows that a single piece of knowledge may contribute to both scientific research and useful commercial applications (the "Pasteur's quadrant").[2] Alternatively, the researcher may decide to develop prior research into a commercially valuable innovation. If he does so, however, the researcher forgoes the opportunity to undertake new research and therefore

[1] For a description of how large research-intensive organisations measure success and provide incentives for the different "tiers" of the R&D firm (i.e. from pure research to development), see Hauser and Zettelmeyer (1997).

[2] This line of research started with Stokes (1997). The canonical example is the French chemist Louis Pasteur, who, acting as a consultant for the French wine industry, confirmed the germ theory of disease. Murray (2002) provides a more recent case study of the "oncomouse", a discovery that was also a product, and fundamentally affected the pace and direction of genetic cancer research. Following Murray (2002) and Murray and Stern (2007) we posit that papers and patents encode the same piece of knowledge.

the chance to have a new idea in that period.

We analyse, in the first place, how scientific and market incentives affect the allocation of a researcher's time between research and development. Not surprisingly, higher commercial rewards induce the researcher to develop more and therefore to spend less time on research. We argue, however, that the introduction of commercial objectives also affects the choice of research projects. At least according to one measure, researchers should have incentives to conduct more basic research, contrary to what the "skewing problem" would suggest. Indeed, we show that the introduction of commercial rewards prompts researchers to increase the search for (ex-post) high-quality ideas, which are more likely to be generated through (ex-ante) riskier research programs. Although risk is associated with all forms of research, high uncertainty is an inherent characteristic of basic research. As Nelson (1959) states in his seminal paper, "moving from the applied-science end of the spectrum to the basic-science end, the degree of uncertainty about the results of specific research projects increases". As documented by Hauser and Zettelmeyer (1997), managers of R&D firms also think that basic research is the most uncertain one.

We also characterise the optimal incentive scheme for research workers. Although universities and research-intensive firms have different objectives, both of them can now use commercial and scientific incentives to motivate and induce their researchers to spend an optimal amount of time in research, on the one hand, and in development, on the other. We show that organisations should use a high level of commercial incentives for researchers at both ends of the scale of intrinsic preferences for research. For those with strong preferences, the organisation needs to induce more development. For those with weak preferences it needs commercial rewards to provide incentives to work. We show that R&D firm's profits at the optimum might also have an inverted-U-shape relationship with respect to the intrinsic preferences for research. This means that it might be optimal, even for non-scientific-oriented organisations, to recruit scientists with some taste for science. At the same time, though, it might be optimal to ban or limit the publications for researchers with strong intrinsic preferences for research.

Our basic model can accommodate fields or disciplines in which ideas have (ex-ante) high scientific value and little commercial interest, or vice-versa. Within a given discipline, however, a given (ex-post) idea of higher scientific value also has higher commercial

value. In reality, there are ideas with a low scientific value and a high commercial value and vice-versa in the same field (falling therefore outside the Pasteur's quadrant). For instance, the synthesis of human insulin (a major commercial achievement) was obtained by Genentech researchers through a method which was rather uninteresting from a scientific point of view. In contrast, around the same time, Harvard researchers tried to synthesize human insulin through methods with a higher scientific novelty, but which made it more difficult for them to achieve the commercially relevant results (Stern, 1995). Another example can be found in the works of Peter C. Doherty and Rolf M. Zinkernagel, who were awarded the 1996 Nobel Prize for the discovery of how the immune system recognises virus-infected cells. Although there have been no commercial gains from their discoveries, they are highly relevant to clinical medicine. To accommodate the potential ex-post differences between scientific and commercial value, we consider an extension with random development value and a three-period version of our basic model. At the same time, the three-period model allows us to study deadline effects, which would appear if the researcher is close to retirement, for example.

To the best of our knowledge, this is the first paper that analyses the impact of the introduction of commercial incentives on the choice of research projects.[3] Lacetera (2006) compares the incentives of academic and industrial researchers to perform additional, cost-reducing research into a given project prior to commercialisation. In his paper, the unit of analysis is a single project and once the project is completed, no other projects are available. In our model, the researcher does not choose whether to do more research on the project. Rather, he faces the trade-off between commercialising the *current* idea and dropping it and venturing into a *new* research project of uncertain quality.[4] In this

[3]We are concentrating on early-stage research. Aghion et al. (2008), instead, study the respective advantages and disadvantages of academia and the private sector at different stages and show that university researchers are more effective at an early stage. Using a closely related model Lacetera (2008) studies firms' determinants to outsource research projects to academic organisations, focusing instead on duration and breadth.

[4]Several papers have analysed the relations between university and the industry. Macho-Stadler et al. (1996) and Jensen and Thursby (2001), for example, analyse the optimal contract between a university and a company. Banal-Estañol et al. (2008) estimate the impact of industry collaboration on academic research output.

sense, our paper is complementary to his. He finds that a greater focus on commercialisation can lead to additional research into a project and we find that the introduction of commercialisation can lead to more intensive research for ex-post path-breaking innovations. Thursby et al. (2007) analyse the impact of licensing on the time spent on basic and applied research in a life cycle context. They show that basic research does not need to suffer from licensing if one assumes that basic and applied research efforts are complementary.

We believe that this paper is also the first to characterise the optimal provision of commercial and scientific incentives in a dynamic context. Our model shares some features with the static moral hazard models in which the agent simultaneously performs multiple tasks. This setup, first analysed by Holmstrom and Milgrom (1991), has been applied to research and development by Cockburn et al. (1999a). These papers identify complementarities between research and development. Our model, as opposed to theirs, is dynamic, and explicitly recognises the trade-off between allocating time to one activity or the other in each point in time.

The remainder of the paper is organised as follows. Section 2 introduces the basic model and Section 3 studies the optimal allocation of time between research and development. Section 4 analyses the choice of research projects. Section 5 characterises the optimal contract. Section 6 analyses a finite version of our basic model that allows us to study deadline effects. Finally, Section 7 concludes. All proofs are relegated to the Appendix.

2 Basic Model

Consider the following repeated model of a risk-neutral researcher. In each period, he spends his time either doing research or being involved in further development of prior knowledge. If he pursues research he obtains, at the end of the period, an "idea" of random quality q, drawn from an independent and identical distribution $F(q)$, density $f(q) > 0$ for all q, expected value $\overline{q}$, and support $[0, Q]$. As stressed by this formulation, the outcome q of research project $F(q)$ is inherently uncertain.

In line with recent literature in the economics of science (Murray and Stern, 2007),

the research output might have scientific and commercial value. The scientific content is publishable in a scientific journal and does not jeopardise further patent rights.[5] The researcher derives a utility of αq, where α denotes the marginal benefit of the quality of the publication to the researcher. This parameter may reflect the puzzle joy, tenure, peer recognition concerns and/or the possibility to obtain monetary prizes or funding from public grants.

In the following period, the researcher may undertake a new research project and obtain, at the end of the period, a new idea. Alternatively, he might decide to spend time in the commercial development of the previous period's output. This might involve patenting and finding and collaborating with a licensing firm to develop a commercially valuable innovation. Or, it could consist of doing consultancy, in being involved in a spin-off or in spending time in any activity related to the scientific output that would allow him to obtain extra financial gains from the discovery.

At the end of the development period, the commercial value of an output of quality q is $\mu q - A$. The parameter μ may be linked to the discipline; academic research in engineering, for example, may have a higher μ than in physical sciences. The parameter A reflects the cost of turning the innovation into a commercial product or, in the case of academic research, the difficulty of finding a company interested in licensing inventions. This cost is net of those commercial values which are not related to the quality of the idea.[6] We assume that the commercial value is an increasing function of the quality of the ideas (i.e. $\mu > 0$) and that ideas of the lowest quality do not have commercial value (i.e. $A > 0$), while the ones of the highest quality do ($\mu Q > A$). In our basic setup, the applicability factors μ and A are certain. As discussed in Section 4, it would be equivalent to assume that they are random, as long as the realisations are not observed until the end of the development period. In Sections 4 and 6 we discuss the cases in which the

[5] We discuss at the end of Section 3 what happens if a scientific publication is delayed by commercialisation. Further, publications do not have strategic effects in our setup. If there was competition between researchers, publishing could also be used as a strategic instrument to affect the R&D race (see for example Bar, 2006).

[6] These fixed benefits should have already been subtracted from the fixed costs. We are assuming that the benefits do not outweigh the costs, avoiding the possibility that the worst commercial ideas are developed. Relaxing this assumption, though, would only create an extra case in Proposition 2 below.

researcher observes μ and A, respectively, at the end of the research period.

When selling the innovation the researcher receives a share s ($\in (0,1)$) of the commercial benefits of the innovation. This can be interpreted as the share that the institution is paying to the scientist, or as the revenue from commercialisation net of the overhead charge, or "Compton Tax", when the researcher is the residual claimant. In the case in which the development period represents the involvement in a spin-off, A could be interpreted as the sunk-cost of creating the spin-off and s as the shares received by the researcher (see for example, Macho-Stadler et al., 2008).[7]

As the survey results of Jensen et al. (2003) confirm, even academic researchers need to be involved in development to ensure commercial success. We assume that without this period of development, the idea does not have commercial value. By being involved in development, however, the researcher forgoes the opportunity to undertake new research and to receive a new idea in that period. In our setup, thus, the conflict between scientific reward and commercial gains only appears in terms of the time that development subtracts from conducting research. Research is motivated both for fundamental scientific interest and commercial gain (pertaining thus to the "Pasteur's quadrant"). In our basic model, the quality of the publications and the quality of the technology developed are positively correlated.

This model is infinitely repeated and time is discounted by δ ($\in (0,1)$). Indeed, an infinite horizon setup is appropriate if after each period the researcher believes that the model will continue for an additional period with some probability. Another advantage of this formulation is that our results are not distorted by the existence of a final date. This model, however, is not dynamic in the sense that there are no differences between periods, i.e., there is neither learning from past research nor accumulation of capabilities over time. While these dimensions are important, the main part of the paper aims, as a first step, at studying the simplest situation where researchers are confronted with the research versus development decision. In Section 6, we consider a finite version of our basic model, which

[7] We are assuming that, when sold, the quality of the innovation is verifiable. The literature on markets for technology suggests the use of a menu of fixed fees and royalties or equity to signal the quality of the invention or to separate bad applications of the technology from good ones (Gallini and Wright, 1990, Macho-Stadler and Pérez-Castrillo, 1991, and Beggs, 1992).

allows us to study deadline effects (as they would appear if, for example, the researcher is close to retirement) and, at the same time, to consider non-stationary research and development outcomes.

3 Time Allocation

After obtaining an idea q in the previous period the researcher decides, at the beginning of the new period, whether to develop this idea further or to work on a new research project. Before characterising the optimal allocation of time as a function of the exogenous parameters, we first state the optimal decision as a function of an exogenous "research continuation value" V. We define V as the discounted present expected value of the utility stream of a researcher at the beginning of a period in which he does research.

Lemma 1 *For any research continuation value V, there is a unique $q^{\circ}(V)$ such that the researcher will not develop if and only if $q \leq q^{\circ}(V)$.*

For any exogenous continuation value, the researcher switches to a new research project unless the output of the previous period has enough commercial prospects. We are now ready to characterise the cut-off q° and present value V as a function of the exogenous parameters of the model.

Proposition 2 *The optimal decision of the researcher is not to develop research output whose quality $q < q^{\circ}$, where q° is defined as follows:*

(i) $q^{\circ} = Q$ *when* $\alpha\overline{q} \geq s(\mu Q - A)$.

(ii) $s(\mu q^{\circ} - A) = \alpha\overline{q} + \delta s\mu \int_{q^{\circ}}^{Q} (x - q^{\circ})\, dF(x)$ *when* $\alpha\overline{q} < s(\mu Q - A)$.

The discounted present expected value V for the researcher is,

$V = \frac{1}{1-\delta}\left[\alpha\overline{q} + \delta s\mu \int_{q^{\circ}}^{Q} (x - q^{\circ})\, dF(x)\right]$.

Intuitively, if the scientific value of the average publication is, in monetary terms, higher than the payment from the best innovation, the researcher will never develop an idea (case i). If this is not the case, then the researcher will develop his best ideas while dropping the worst ones (case ii). The quality, to which the researcher is indifferent, is such that the monetary reward after development is equal to the expected opportunity

cost of a period's time; namely, the scientific reward of the average publication plus the expected monetary reward from an innovation derived from a research output of higher quality.

This proposition allows us to pin down which changes in the exogenous parameters induce the researcher to develop more often; that is, when the region of case (i) (in which he never develops) shrinks and/or when the threshold of case (ii) (above which he develops) is lower.

Corollary 3 *The researcher develops more often, when*
(i) the applicability factor, μ, increases;
(ii) the net costs of turning an innovation into a commercial product, A, decrease;
(iii) the discount factor, δ, decreases;
(iv) the marginal utility of the quality of the publication, α, decreases;
(v) the share of the benefits received by the researcher, s, increases.

As one would anticipate, a higher marginal commercial value of the innovation, μ, and a lower cost of turning the innovation into a commercial product, A, induces more development. Indeed, the empirical results by Thursby and Thursby (2007) confirm that the probability that an academic researcher discloses a patent in a given year is higher in more applied fields, such as engineering, and in fields in which the results are in strong demand by the industry, such as biological sciences.

More interestingly, if the future carries little value (δ low), then researchers do not lose much from developing in this period and foregoing the possibility of obtaining a better research outcome. As a result, less patient researchers develop more often. An alternative interpretation of the discount rate δ is the rate at which ideas are obtained. The corollary implies that a more prolific scientist (higher δ) should be more reluctant to develop a given idea. Although he might end up developing more or less in total, the commercial value of his average innovation should definitely be higher.

Finally, stronger commercial incentives (a higher s) and a lower emphasis in publications (a lower α) induce more development. Although the combination (α, s) is exogenous to the researcher, the organisation determines s and can also affect α, offering, for example, publication prizes. As we argue in Section 5, the optimal combination also depends

on the organisation' objectives.

4 Project Selection

We now turn to the controversial question of how the introduction of commercial remuneration affects the choice of research projects ($F(\cdot)$). As we shall see in this section, whether the researcher chooses more basic or more applied projects hinges crucially on how basicness is defined. One of the potential differences between basic and applied projects is that basic projects are riskier than applied projects (Nelson, 1959; Hauser and Zettelmeyer, 1997). But, another potential difference is that the outcomes of basic projects might, in expected terms, be more difficult to commercialise and might carry higher scientific reward. We shall consider each of these two distinctions in turn.[8]

4.1 Level of Risk

According to Nelson (1959), when moving from the applied-science to the basic-science end of the spectrum, the degree of uncertainty about the results of specific research projects increases. In what follows, we will show that according to this distinction, researchers would be more willing to choose projects that are more basic in nature if they were to receive a share of the financial profits from commercialisation. In order to isolate the effects of this difference, suppose that the researcher can costlessly choose the level of risk of his research projects, assuming that the mean and the support of the distribution are identical.

Proposition 4 *The introduction of remuneration for commercial inventions induces researchers to select riskier projects. By choosing riskier projects, researchers are more reluctant to develop a given outcome, although they might develop more or less in expected terms.*

[8]Other papers have also analysed project selection when projects differ on their variance. In Cabral (2003), for example, two firms competing in R&D have to strategically choose between two projects, one of which is a mean-preserving spread of the other. Other distinctions between basic and applied research are also possible. Basic research projects can have a broader set of applications or, similar to our second definition, be characterised by a lower probability of commercial success.

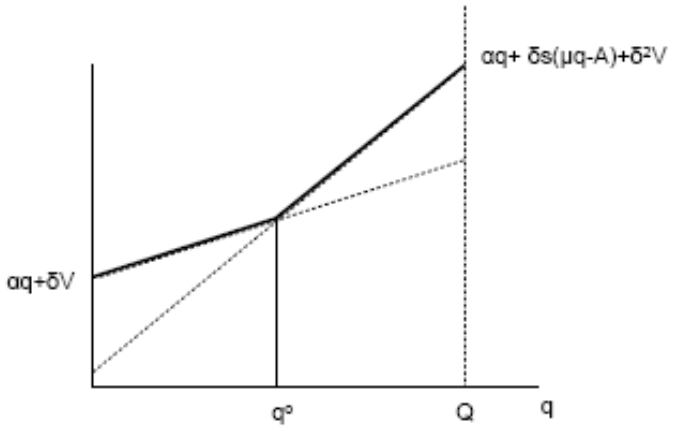

Figure 1: Researcher's utility in a given period (for a given V) as a function of the quality of the idea.

The intuition behind the preference for the risky project follows from the fact that the researcher acts as if he was risk-loving with respect to the quality of the output. As we can see in Figure 1, the researcher's utility as a function of the output quality is a convex function. Indeed, for a given V, the utility is the maximum of two affine functions that represent the value from continuing to do research ($\alpha q + \delta V$) and the value from development ($\alpha q + \delta s\left[\mu q - A\right] + \delta^2 V$). The latter is steeper because better output has a higher development value. The former has a higher intercept because the researcher obtains a new idea sooner. As shown in Proposition 2, as long as the remuneration for the best innovation is high enough, the two lines cross at some point q^o.

By choosing riskier projects, researchers are more reluctant to develop a given idea. Indeed, they are more likely to obtain a better idea in the next period and they are therefore more willing to drop the current one. As shown in Figure 2, though, they might end up developing more ideas in expected terms. Although $F^+(x)$ is a mean-preserving spread of $F^-(x)$ and therefore the threshold for the former is higher ($q^{+o} > q^{-o}$), the ex-ante probability of developing is also higher ($F^+(q^{+o}) < F^-(q^{-o})$).

Although the scientific and commercial rewards were assumed to be linearly increasing in the quality of the output, this result should hold more generally. Indeed, the introduction of commercial rewards induces the researcher to select between two increasing

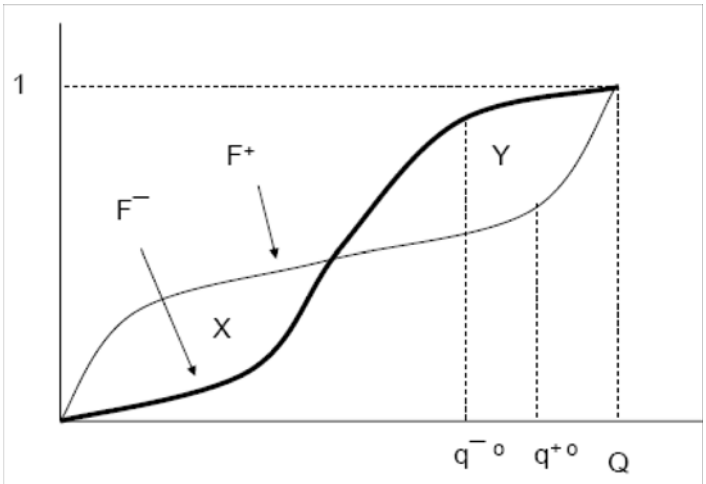

Figure 2: Distribution $F^{-}(\cdot)$ and a mean preserving spread, $F^{+}(\cdot)$ (Area X=Area Y).

functions. Assume that the commercial value of an idea of quality q is $\mu(q)q$. Given that the best innovations have a much higher value than intermediate ones, $\mu(q)$ would typically be not constant as in our model but increasing. This would make the researcher even more risk-loving than with no commercial rewards. Furthermore, researchers would also select riskier projects even if the value of the publications is given by $\alpha(q)q$ for any $\alpha(q)$, and not only when $\alpha(q)$ is constant. Indeed, although he might not always act as if he was risk-loving he would exhibit more risk-loving behaviour than before the introduction of commercial rewards.

4.2 Scientific and Commercial Value

Another potential difference between basic and more applied research is that the outcomes of applied projects can be more easily commercialised. In other words, the net costs A of turning the innovation into a commercial product are lower. At the same time, peer recognition and the expected value of publication (measured by the parameter α) can be lower for more applied projects. The next proposition confirms that, according to this distinction, researchers will be more likely to choose applied projects in the presence of commercial incentives.

Proposition 5 *The introduction of remuneration for commercial inventions is conducive*

to a selection of projects with lower costs of development and lower scientific value. By choosing these projects, researchers spend more time in development and less in research.

Although the effects of each of the two definitions are different, the definitions are not mutually exclusive. If basicness is characterised by both higher risk *and* higher development costs and scientific value, the effect of commercial rewards is ambiguous. Of course, if more applied projects have much lower development costs, then researchers would choose more applied research projects even if they are less risky. On the other hand, researchers would choose research projects that are riskier if the difference in development costs is not too large. All in all, the introduction of commercial incentives does not necessarily "skew" research towards more applied projects.[9]

4.3 Extensions

Our basic model assumes that the development factor is certain. But it also allows for the possibility that it is random, as long as the realisation is not observed until the end of the period of development. Both are equivalent given that only the expectation (and not the realisation) is relevant for the time allocation decision.

In Banal-Estañol and Macho-Stadler (2007), we consider an extension with random development value. The researcher realises the commercial value of a piece of knowledge at the end of the research period, when he also realises its quality. This extension allows us to consider ideas that have, ex-post, low scientific value and high commercial interest and vice-versa (falling therefore outside the Pasteur's quadrant). We show that ideas that turn out to have high commercial value are more likely to be developed. The introduction of remuneration still induces researchers to choose riskier projects in terms of quality. Furthermore, it would also induce researchers to choose projects that have a riskier commercialisation value.

In the basic model, we also assumed that the decision to develop did not affect the timing of the publications. However, there is evidence that publications of results that

[9] An important consideration for social welfare, which is beyond the reach of our model, is whether several researchers would be pushed to select the same project. This might still be optimal if the duplication of efforts increases the likehood of having a good discovery.

have been the subject of a patent application might be delayed (Geuna and Nesta, 2006). Suppose that if the researcher develops, then he cannot publish the scientific content until the end of the development period. The researcher would develop less often, given that the delay makes development less attractive. But, as shown in detail in Banal-Estañol and Macho-Stadler (2007), the results are qualitative the same. The introduction of commercial incentives still induces research that is riskier. The effect, however, is weaker than without delay.

5 Management of R&D Activities

Research organisations need to motivate researchers and ensure that they allocate an "optimal" amount of time to research and development. In this section, we analyse the optimal incentive scheme for an organisation that could use commercial and scientific incentives. We assume that the researcher works in a predetermined pool of projects and we thus abstract the problem of project selection. But, we extend our analysis to allow for the possibility that the researcher does not exert much effort. The scientist decides whether to exert effort or "work", and if so, whether to do research or commercialise as before.

To be more precise, we assume that if the researcher works in a given period, either in research or development, he incurs a cost c. Alternatively, he can decide to not perform an activity, at a 0 cost. We assume that effort is not verifiable and therefore not contractible. This implies that the scientist cannot be compelled to provide effort, she has to be motivated to supply it. On the other hand, we assume again that the scientific results and the commercial revenue are observable and contractible, but the "stopping rule" (time allocation) is not. The researcher cannot be forced to stop doing research and commercialise at a particular point, he has to be induced to do so.

5.1 The Optimal Contract

The organisation pays the researcher through a contract (s, α^+), where s $(\in [0,1])$ is his share of the commercial revenues and α^+ (≥ 0) is a prize (in monetary terms) awarded

to the quality of the research, in addition to his intrinsic puzzle joy or peer recognition, α^o. That is, we decompose the marginal benefit of the quality of the publications α as $\alpha \equiv \alpha^+ + \alpha^o$. As a result, a given researcher's α depends on the organisation he works for. Note that in what follows we can ignore the researcher's participation constraint because it can be guaranteed through a fixed transfer, if necessary.

As mentioned in the introduction, research organisations differ as to what importance they attach to scientific results versus commercial value. We denote the relative weight that the organisation attaches to publications as $\rho \in [0, \infty)$ whereas the (normalised) weight attached to the organisation's share of the commercial applications is 1. We are thus omitting the uninteresting case in which the organisation is only concerned with publications. Higher values of ρ imply a higher concern for scientific reputation or prestige from successful research and a lower importance of commercial profits.

As we did for the researcher, we denote the discounted present expected profits for the organisation at the beginning of a period in which the researcher does research as B.

Lemma 6 *Assuming that the researcher exerts effort in each period, the discounted present expected value B for the organisation is*

$$B(\alpha^+, s) = \frac{(\rho - \alpha^+)\overline{q} + \delta(1-s)\int_{q^\circ}^{Q}(\mu x - A)\,dF(x)}{(1-\delta)\left(1 + \delta\left[1 - F(q^\circ)\right]\right)},$$

where q° is defined in Proposition 2.

The organisation obtains its discounted value of the average publication less the discounted average scientific monetary prize awarded to the researcher (first term in the numerator) plus a share $(1-s)$ of the potential financial benefit for developing and selling an idea of high quality, $q > q^\circ$, in the following period (second term in the numerator). Time is discounted by δ (first term in the denominator) and by the possibility of not doing research in that period (second term in the denominator). The expression for the value for the organisation (B) is similar to that of the researcher (V), defined in Proposition 2 (especially when expressed as in (2), in the proof).

During a research period, the researcher devotes effort, assuming he will also do so in the future, if and only if his expected utility from working, $V - c$, is greater than his

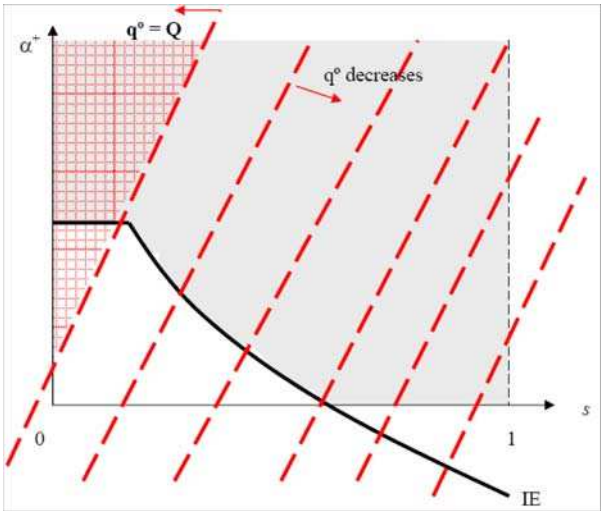

Figure 3: The isolevel dashed curves represent the time allocation constraint (TA) for a given q^o. The isolevel curve for $q^\circ = Q$ is the thick-squared region. The shadowed area represents the contracts satisfying the incentive to provide effort constraint (IE).

expected utility from not exerting effort, $0 + \delta V$. Consequently, the "incentive to provide effort" constraint (IE hereafter) can be written as

$$\left(\alpha^o + \alpha^+\right) \overline{q} + \delta s \mu \int_{q^\circ}^{Q} (x - q^\circ)\, dF(x) \geq c, \tag{IE}$$

where q° (to which we will refer as the "time allocation" constraint or TA) is again defined in Proposition 2.

Figure 3 represents the TA and IE constraints. The time allocation constraint for any q° is represented by the isolevel dashed curves. The isolevel curve for $q^\circ = Q$, in which the researcher never develops, is the thick squared region. The set of contracts satisfying the IE is the shadowed area. For each cost level c, the IE constraint implicitly defines a family of contracts (s, α^+) that induces the researcher to provide effort. Commercial and scientific incentives are substitutes and therefore the boundary curve, in terms of α^+, is a non-increasing function of s. By providing higher research incentives, the organisation can offer a lower share of the commercial profits. If α^+ is high enough, it is not necessary to increase s further, though.

The following lemma characterises the set of contracts that induces the researcher to

provide effort.

Lemma 7 *The contracts* (s, α^+) *that induce the researcher to provide effort...*
(i) are the set of all feasible contracts if $c \leq \alpha^o \overline{q}$*;*
(ii) satisfy $s > s^m \equiv \frac{\alpha \overline{q}}{(\mu Q - A)}$ *or* $\alpha^+ > 0$ *(or both) if* $c > \alpha^o \overline{q}$*.*

From the IE constraint, if $\alpha^o \geq c/\overline{q}$ the researcher would provide effort for any s and α^+, thanks to the intrinsic value from scientific research. If, instead, $\alpha^o < c/\overline{q}$ the incentives should be provided either via α^+ or via s. If, for example, $\alpha^+ \geq c/\overline{q} - \alpha^o > 0$ the researcher would provide effort for any s, thanks to the scientific value of the publications. If, instead, $c/\overline{q} - \alpha^o > \alpha^+ \geq 0$, the organisation needs to provide $s > s^m$ to induce *some* commercialisation and therefore positive financial benefits from development. All contracts that specify $s \in [0, s^m]$ are, in practice, identical because they do not induce commercialisation (see Proposition 2). Therefore, without loss of generality, we will reduce the set of feasible shares to $s \in [s^m, 1]$ from now on.

The organisation's problem is in choosing the optimal contract (s, α^+) in order to maximise B subject to the IE, TA and the feasible intervals for α^+ and s,

$$\begin{aligned} \max_{s,\alpha^+} \quad & B(\alpha^+, s) \\ \text{s.t.} \quad & TA,\ IE,\ s^m \leq s \leq 1,\ \alpha^+ \geq 0. \end{aligned} \tag{1}$$

In order to present the solution of the problem, let us denote q^e the stopping rule that maximises the total surplus, $B+V$. Further, define s^e and α^{+e} the "unrestricted" contract that induces q^e and satisfies IE with equality (s^e and α^{+e} might not be within the feasible bounds of α^+ and s).

Proposition 8 *The optimal incentive scheme* (α^{+*}, s^*) *satisfies:*
(i) For $c \leq \alpha^o \overline{q}$ *then,* $\alpha^{+*} = 0$ *and* $s^m \leq s^* \leq 1$*.*
(ii) For $c > \alpha^o \overline{q}$ *then*
(ii.1) $\alpha^{+*} = \alpha^{+e}$ *and* $s^* = s^e$ *if* $s^e \leq 1$ *and* $\alpha^{+e} \geq 0$*,*
(ii.2) $\alpha^{+*} = \alpha^c$ *and* $s^* = 1$ *if* $s^e > 1$*,*
(ii.3) $\alpha^{+*} = 0$ *and* $s^c \leq s^* \leq 1$ *if* $s^e \leq 1$ *and* $\alpha^{+e} < 0$*,*

where α^c *and* s^c *are implicitly defined by*

$$(\alpha^c + \alpha^o)\overline{q} + \delta\mu \int_{q^\circ}^{Q} (x - q^\circ)\, dF(x) = c \text{ and } \alpha^o\overline{q} + s^c\delta\mu \int_{q^o}^{Q} (x - q^o)\, dF(x) = c.$$

Figure 3 also helps to understand the results in Proposition 8. An organisation can obtain the same revenue at a lower cost by decreasing s and α^+ simultaneously, provided that it keeps q° constant. Hence, (α^{+*}, s^*) has to be such that IE is binding or it is in a corner solution for α^+ or s. If $c \leq \alpha^o\overline{q}$ (case i) any contract satisfies the IE constraint and is therefore never binding (Lemma 7). The organisation chooses a contract on the horizontal axis, i.e. it does not allocate extra incentives to scientific results ($\alpha^+ = 0$) and sets the share s in order to maximise B given TA and $\alpha^+ = 0$. If the organisation is only interested in inducing research, the optimal contract would have minimal shares for the researcher ($s^* = s^m$). But if the organisation is interested in inducing *some* development then it will include additional shares ($s^* > s^m$).

If $c > \alpha^o\overline{q}$, and the socially optimal stopping rule can be achieved with a feasible contract satisfying IE, then this contract will be the solution (case ii.1). If this contract is not feasible, i.e. if $s^e > 1$ or $\alpha^{+e} < 0$, the organisation will choose a contract in the boundaries of the space of feasible parameters, either by giving all the commercial rewards to the researcher (case ii.2) or by giving him no extra scientific incentives (case ii.3). In the latter, the organisation will, as in case (i), choose the optimal s in order to maximise B given TA and $\alpha^+ = 0$.

5.2 Comparative Statics

We now explore how the optimal incentive scheme is affected by the researcher's characteristics and the organisation's objectives. The following corollary shows how the organisation needs to adapt its incentive scheme to the researcher's level of intrinsic motivation to perform research.

Corollary 9 *Suppose that* q *is uniformly distributed on* $[0, 1]$. *Then, there exists* $\overline{\alpha}^o (< 2c)$ *such that for* $\alpha^o < \overline{\alpha}^o$, *the optimal share* s^* *is decreasing in* α^o. *If* $\alpha^o > 2c$, *the optimal share* s^* *is increasing in* α^o *for* $\rho < \overline{\rho}(\alpha^o)$ *and* $A = 0$.

Interestingly, organisations should use a higher level of commercialisation shares for sufficiently high but also for sufficiently low levels of intrinsic research interest. For high levels of α^o, the organisation needs to use a high s to induce development while for low levels of α^o, the organisation needs to use a high share to provide incentives to work.

In order to further illustrate how the optimal incentive scheme changes with the parameters, in Table 1 we present a numerical example based on a pool of ideas following a uniform distribution over the interval $[0, 1]$ with $\mu = 2$, $A = 0$, $\delta = 0.4$. The first two blocks show again how the optimal contract, the organisation's profits and the stopping rule (rows 3 to 6) change with α^o (row 2). Block 1 considers an organisation exclusively interested in commercial revenue and Block 2 an organisation that weights commercial revenue and scientific reputation equally. Given that $c = 0.1$, we are in case (i) of Proposition 8 if $\alpha^o \geq 0.2$ and in case (ii) if $\alpha^o < 0.2$.

	$\alpha^o(\rho = 0, c = 0.1)$			$\alpha^o(\rho = 1, c = 0.1)$			ρ (α^o= 0.1, $c = 0.1$)			c (α^o= 0.1, $\rho = 0$)			
	0.5	0.2	0	0.5	0.2	0.0	0	2	≥ 4	0.02	0.06	0.1	0.4
α^{+*}	0	0	0	0	0	0.15	0	0.08	0.1	0	0	0	0.2
s^*	0.27	0.15	0.34	0.22	0.11	0.15	0.21	0.09	≤ 0.04	0.09	0.09	0.21	1
B^*	0.30	0.38	0.32	1.01	1.06	0.96	0.38	1.71	3.25	0.42	0.42	0.38	-0.12
q°	0.50	0.40	0.15	0.59	0.49	0.34	0.2	0.5	1	0.35	0.35	0.23	0.2

Table 1: Optimal contract (α^{+*}, s^*), maximum profits (B^*) and stopping rule (q^o) for a uniform distribution over $[0, 1]$ $(F(x) = x)$ with $\mu = 2$, $A = 0$ and $\delta = 0.4$.

An organisation that is not concerned with scientific reputation ($\rho = 0$) will not use research prizes to induce effort (Block 1). The incentives to work will be induced with the commercialisation shares, which also give incentives to develop. An organisation that has the same interest in commercialisation and in scientific reputation ($\rho = 1$) will use both commercial and scientific incentives to motivate a researcher with low intrinsic interest to publish (last column of the second block). As shown in the previous corollary, organisations use a high level of commercialisation shares for high and for low levels of intrinsic research interest. The table also shows that the organisation's profits at the

optimum have an inverted-U-shape with respect to α^o. This means that, even non-scientific-oriented organisations ($\rho = 0$) can find it optimal to hire a scientific-oriented researcher ($\alpha^o > 0$). A researcher who is much too research-driven, though, can also lower profits.

The third block highlights how the optimal contract changes with ρ (second row). A highly research-oriented institution (high ρ), may decide to avoid commercialisation in equilibrium (e.g. if $\rho \geq 4$ in our example). The researcher receives extra recognition for scientific output but he is induced to not commercialise ($s^* = s^m = 0.04$). Comparing the stopping rules, more commercial-oriented institutions will intuitively induce a lower threshold, q°.[10] But, even for the organisations that are exclusively interested in commercial revenue, it is never optimal to induce the researcher to develop every idea. Poor ideas (low q) are better abandoned.

The fourth block illustrates how the optimal contract changes with c (second row). If $c = 0.02$ (first column) every contract satisfies the incentive to exert effort constraint. The optimal contract corresponds to the case (i) of Proposition 8 in which s^* is interior. For $c = 0.06$ the organisation could choose the s that makes the incentive to exert effort (IE) binding, s^c. However it does not. It is still optimal to choose the same contract as in the first column (which would now satisfy $s^* > s^c$) (case ii.3). If $c = 0.1$, the IE is binding in equilibrium and the contract includes a share s that decreases with c (case ii.1). Finally, if the costs are very high ($c = 0.4$) even for $s = 1$ the incentive constraint to exert effort would not be satisfied unless $\alpha^+ > 0$ (case ii.2). The researcher keeps all the revenue from commercialisation and, in addition, he has to receive a prize for publications in order to have an incentive to work. If there are no other benefits from hiring the researcher (except those included in B), the organisation might be better off not hiring the researcher, given that $B^* < 0$.

Our model assumes that organisations cannot prevent researchers from enjoying pure research results and therefore α^+ has to be non-negative. A negative α^+ would involve prohibiting publications or asking the researchers to pay for their publications (in future wages, for example). Although the former might have involved extra costs for the

[10] According to our definition of B, it does not make sense to compare the absolute profits B^* for different values of ρ since, for any given contract, an organisation with a higher ρ generates more profits.

organisation, the latter might have generated further revenues. Suppose here that it is possible to set a negative α^+ and that this does not involve extra costs or revenues. Table 1 shows that it might indeed be optimal to set a negative α^+. Block 1 shows that a commercially-oriented organisation ($\rho = 0$) increases profits by reducing the researchers' intrinsic interests to publish from $\alpha^o = 0.5$ until $\alpha^o = 0.2$ or $\alpha^o = 0$. An effective reduction of α^o can be obtained with a negative α^+. By allowing α^+ to be negative, the optimal contract always belongs to cases (ii.1) or (ii.2) of Proposition 8.

6 Retirement Effects

In this section we consider a three-period version of our basic model, which allows us to study deadline effects. These effects would appear if the researcher is close to retirement, for example. At the same time, it enables us to consider non-stationary research and development outcomes. We also allow for the possibility that the net costs of development, which include the difference between the scientific and the additional commercial value (on top of the random quality of the idea), are random, with positive or negative realisations.

Formally, the quality and the net costs of development, q_i and A_i, are uncertain at the beginning and realised, at the same time, at the end of each research period. Although the game has three periods, the third period may be different depending on whether the researcher spent the second one in research or in development. Accordingly, allowing past experience to matter, we denote the nodal points as i, $i = 1, 2, 3, 3'$. We assume that the variables q_i and A_i are distributed independently according to $G_i(q)$ and $H_i(A)$ on the support $[0, Q_i]$ and $\left[\underline{A}_i, \overline{A}_i\right]$, respectively, where $\underline{A}_i < 0$ and $\overline{A}_i > 0$. Similarly, we denote the researcher's marginal benefit of the quality of research and his share of commercial revenues in period i as α_i and s_i, respectively.

In this model, the researcher needs to make a time allocation decision at most twice, after the first research outcome, (q_1, A_1), and after the second, (q_2, A_2), in the case in which he undertakes research in that period.

Proposition 10 *The optimal decision of the researcher is not to develop research output whose quality and net costs of development* (q_i, A_i) *(*$i = 1, 2$*) are such that* $A_i > \widehat{A}_i(q_i)$,

where $\widehat{A}_i(q_i)$ *are implicitly defined by*

$$s_3(\mu z - \widehat{A}_2(z)) = \alpha_{3'}\overline{q}_{3'} \text{ and } s_2(\mu z - \widehat{A}_1(z)) = K(\widehat{A}_2(q_2)),$$

where $K(\widehat{A}_2(q_2))$ *is defined as*

$$\alpha_2\overline{q}_2 - \delta\alpha_{3'}\overline{q}_{3'} + \delta s_3 \int_0^{Q_2} \int_{\underline{A}_2}^{\widehat{A}_2(x)} (\mu x - y) dH_2(y) dG_2(x) + \delta\alpha_3\overline{q}_3 \int_0^{Q_2} (1 - H_2(\widehat{A}_2(x)) dG_2(x).$$

The first condition shows that an increase in s_3 or a decrease in $\alpha_{3'}\overline{q}_{3'}$ enlarges the set of combinations of quality and net costs for which the researcher develops after the second research period. Similarly, the second condition shows that an increase in s_2 or in $\alpha_3\overline{q}_3$ will also enlarge the region in which the researcher stops after the first period.

Corollary 11 *In a stationary environment* ($\alpha_i = \alpha$, $s_i = s$, $H_i(y) = H(y)$, $F_i(y) = F(y)$, *for* $i = 1, 2, 3, 3'$*), the researcher is more likely to develop in the third period than in the second.*

In the last period the researcher is more likely to develop because the opportunity costs of development do not include the loss of a potentially good idea. This result is consistent with the fact that the number of patent disclosures in academia increases with tenure and age, at least until the middle ages (Thursby and Thursby, 2007). We could also interpret a result of the infinite model in a similar way. One could argue that, with tenure and age, the marginal utility of scientific publications decreases, which is shown to induce more development in Corollary 3.

We now turn to the changes in the level of risk. For simplicity, we concentrate on the case in which q is a random variable and A is a parameter (the conclusions for the case in which q is a parameter and A is random are similar). Suppose further that $\mu = 1$ and $A_1 = A_2 = 0$. Notice that a mean preserving spread of $G_3(q)$ and $G_{3'}(q)$ does not affect the time allocation decisions. A mean-preserving spread of $G_1(q)$ does not affect the time allocation decision either but it will affect the present expected value V. As we can see in Proposition 10, $G_2(q)$ affects the time allocation behaviour at the beginning of the second period but not at the beginning of the third.

The next proposition shows first that the result obtained in Section 4 is also true here. Namely, the introduction of commercial rewards induces researchers to choose projects

that have a higher level of risk. Here, we are also able to analyse the marginal incentives to take riskier projects when the share of commercial profits, s_2 and/or s_3, increases.

Proposition 12 *Consider $\mu = 1$ and $A_1 = A_2 = 0$. The introduction of remuneration for commercial inventions induces researchers to select riskier projects. Moreover, the incentives to select ideas from distributions that are mean-preserving spreads of each other:*
i) increase with s_2, and increase with s_3 if and only if $q_1^o > \bar{q}_1$, in period 1,
ii) decrease with s_2, and increase with s_3, in period 2.

This proposition shows that the effects of the researcher's share of commercial profits on the incentives to take riskier projects in periods 1 and 2 are not clear. If the researcher chooses the same research project in both periods (i.e. chooses a research "profile") and the shares change simultaneously in both periods (e.g., if $s_2 = s_3$), the effects are combined and it is difficult to reach a conclusion about the direction. This explains why, in the infinite model, analysing the tendency to select a riskier pool of projects as a function of the share s is difficult to analyse without having particular functional forms.

7 Concluding Remarks

This paper studies the provision of adequate incentives for university and company researchers. Public and private research institutions can use commercial and scientific incentives to motivate researchers and induce them to spend an optimal amount of time in research, on the one hand, and in development, on the other.

To understand researchers' behaviour, we build a simple repeated model of a researcher who can choose between undertaking new research or developing prior research into commercially valuable innovations. We show that, unless the quality of the outcome has enough commercial prospects to compensate for the delay, the researcher should undertake a new research project. The opportunity costs of development and commercialisation include not only scientific output but also the opportunity to obtain a more lucrative innovation. Consistent with the empirical evidence, our comparative statics results indicate that a researcher spends more time developing if his discipline has greater applicability and if the marginal utility of scientific publications is lower.

We also show that the introduction of commercial incentives affects not only the time spent in research and in development but also the choice of research projects. Therefore we are able to analyse one of the "unintended" effects of the Bayh-Dole Act, which increased the incentives to transfer university research to the market. Some groups have expressed concerns about the possibility that academic faculties "skew" the nature of their research, selecting applied rather than basic research projects, and therefore putting the future of the industrial base at stake. We show that the introduction of commercial remuneration pushes the researcher to prefer riskier projects. Given that higher levels of uncertainty are related to more basic research, the introduction of commercial rewards might not only preserve but also enhance the choice of more basic research projects.

Although the choice of research projects cannot be measured directly, existing indirect evidence suggests that the much-feared switch from basic to applied research in academia is not occurring. Thursby and Thursby (2002) conclude that changes in the direction of faculty research seem to be relatively less important than other factors in explaining the increased licensing activity. Thursby and Thursby (2007), as Hicks and Hamilton (1999) earlier, find no systematic change in the proportion of publications in basic versus applied journals between 1983 and 1999. They also report that the total number of publications per faculty member more than doubled over the time period, indicating that the number of publications in basic journals actually increased. A decrease in the quality of university patents could also be taken as an indication of a trend towards more applied research. Although Henderson et al. (1998) do find a decreasing trend in the quality of university patents (measured by the number of forward citations), Mowery et al. (2001), Mowery at al. (2002) and Mowery and Ziedonis (2002) argue that this is due to an increased number of new and inexperienced technology transfer offices rather than to a systemic change in the nature of academic research.

Our model is not only consistent with a variety of stylised facts but it also generates a number of additional testable predictions. First, by choosing riskier projects, researchers would be more reluctant to develop low-quality research. Instead, they are more willing to continue undertaking research because they are more likely to obtain higher-quality results in the future. As a result, it might be that they end up developing less as commercial rewards increase. Indirect evidence from this effect in academia can also be found in

Thursby and Thursby (2007), who state that "the much publicized increase in licensing activity appears to be concentrated among a minority of faculty". Second, the commercial value of developed projects is higher. Again, indirect evidence suggests that most of the patenting revenues are concentrated among a reduced number of patents. Although the level of invention disclosures, patent applications and licenses executed increased by 84%, 238% and 161% respectively from 1991 until 2000, the royalty revenue increased by 520% in the same period. Third, a selection of riskier projects should lead to a more spread distribution of the quality of the publications. Empirically, one could analyse whether the quality of the publications, measured for example in citations, of researchers in departments in which commercial rewards are larger is more spread.

We also characterise the optimal incentive scheme for research workers. We show how universities and research-intensive firms should use commercial and scientific incentives to motivate and induce their researchers to spend an optimal amount of time in research and development. The problem of providing incentives to scientists is related to the problem of providing incentives to the broader group of "knowledge workers", which includes computer programmers, engineers and technology managers (for a recent article on this topic, see Lacetera and Zirulia, 2008). Knowledge workers are meant to create, distribute, and apply knowledge within their organisations. Incentive schemes may be needed not only to induce them to work hard but also to induce them to allocate an optimal amount of time between acquiring new knowledge and developing or transferring it. Like the researchers, not all knowledge workers are alike. Some are more motivated than others to perform certain tasks. But knowledge workers can also be incentivised. It might be possible to include not only a traditional bonus related to the performance of the firm, but also rewards to the acquisition and the creation of knowledge. Examples of the latter include better work environments, access to technologies, and external visibility and recognition for knowledge improvement. A full investigation of this issue is a challenging task for future research.

Appendix

Proof of Lemma 1

The researcher will be able to sell the innovation if the value for the firm is larger than the costs. This defines two intervals, $[0, \frac{A}{\mu})$ and $[\frac{A}{\mu}, Q]$, depending on the value of q. If $q < \frac{A}{\mu}$ then the researcher will not develop for any V since he will never be able to sell anyway, $\alpha q + \delta V \geq \alpha q + \delta^2 V$. If $\frac{A}{\mu} \leq q \leq Q$ then he will be able to sell the innovation if he develops and therefore he will develop whenever $\alpha q + \delta s\left[\mu q - A\right] + \delta^2 V \leq \alpha q + \delta V$, or equivalently, when $(1-\delta)V \geq s\left[\mu q - A\right]$.

Denoting $m(q) \equiv s\left[\mu q - A\right]$, the previous discussion implies that, for all V, $q^{\circ}(V)$ is given by $m(q^{\circ}(V)) = (1-\delta)V$ when $m(Q) > (1-\delta)V$ and $q^{\circ}(V) = Q$ when $m(Q) \leq (1-\delta)V$. Given that $m(Q) > 0$ (by assumption $\mu Q - A > 0$), in order to show that there exists a unique $q^{\circ}(V)$, we need to show that $m(q)$ is an increasing function and $m(0) < 0$. Indeed, $m'(q) = s\mu > 0$ and $m(0) = -sA < 0$.

Proof of Proposition 2

Suppose firstly that the cut-off chosen by the researcher is $q^{\circ} = Q$. The researcher never develops and never sells. Hence $V = \int_0^Q \alpha x dF(x) + \delta V$, which simplifying gives $V = \frac{1}{1-\delta}\alpha\overline{q}$. The decision $q^{\circ} = Q$ is optimal if and only if $(1-\delta)V \geq s\left[\mu Q - A\right]$, which substituting gives $\alpha\overline{q} \geq s\left(\mu Q - A\right)$, which corresponds to the region in case (i).

Suppose secondly that the cut-off chosen by the researcher is $q^{\circ} < Q$. We have that

$$V = \int_0^Q \alpha x dF(x) + \delta F(q^{\circ})V + \delta s \int_{q^{\circ}}^Q \left(\mu x - A\right) dF(x) + \left[1 - F(q^{\circ})\right]\delta^2 V,$$

which, passing all terms in V to the left-hand side of the equality gives

$$\left(1-\delta\right)\left(1 + \delta\left[1 - F(q^{\circ})\right]\right)V = \int_0^Q \alpha x dF(x) + \delta s \int_{q^{\circ}}^Q \left(\mu x - A\right) dF(x).$$

This equality can be rewritten as

$$\left(1-\delta\right)\left(1 + \delta\left[1 - F(q^{\circ})\right]\right)V = \alpha\overline{q} + \delta s \int_{q^{\circ}}^Q \left(\mu x - A\right) dF(x). \tag{2}$$

On the other hand, using the fact that $q^{\circ}(V)$ should be defined here as $(1-\delta)V = s\left[\mu q^{\circ} - A\right]$, we can substitute V by $\frac{s}{(1-\delta)}\left[\mu q^{\circ} - A\right]$, which leads to

$$\left(1+\delta\left[1-F(q^{\circ})\right]\right)s\left[\mu q^{\circ}-A\right] = \alpha\overline{q} + \delta s\int_{q^{\circ}}^{Q}(\mu x - A)\,dF(x). \tag{3}$$

We can rewrite this equation as,

$$s\left[\mu q^{\circ}-A\right] + \delta s\left[1-F(q^{\circ})\right]\left[\mu q^{\circ}-A\right] - \delta s\int_{q^{\circ}}^{Q}(\mu x - A)\,dF(x) = \alpha\overline{q},$$

from there we have that q° is implicitly defined by

$$s\left(\mu q^{\circ}-A\right) - \delta s\mu\int_{q^{\circ}}^{Q}(x-q^{\circ})\,dF(x) = \alpha\overline{q}. \tag{4}$$

Let us now define $j(q)$ as

$$j(q) \equiv s\left(\mu q - A\right) - \delta s\mu\int_{q}^{Q}(x-q)\,dF(x).$$

Since $j'(q) = s\mu + \delta s\mu(1-F(q)) > 0$, the cut-off q° defined by $j(q^{\circ}) = \alpha\overline{q}$ in (4) is unique. Finally, we need to check that $q^{\circ} \leq Q$. Since $j(q^{\circ}) = \alpha\overline{q}$ and $j'(q) > 0$, we need that $j(Q) \geq \alpha\overline{q}$ or $s\left(\mu Q - A\right) \geq \alpha\overline{q}$, which corresponds to the region in case (ii).

Proof of Proposition 4

To prove this result, consider two distributions, $F^{-}(q)$ and $F^{+}(q)$, with the same support $[0,Q]$ and with the same mean $(\overline{q})$, and $F^{+}(q)$ being a mean preserving spread of (i.e. riskier than) $F^{-}(q)$. By definition, $\int u(x)dF^{+}(x) \geq \int u(x)dF^{-}(x)$ for any $u(x)$ defined in R^{+}, non-decreasing and non-concave. Given that $u(x) = 0$ if $x \in [0,q]$ and $u(x) = x-q$ if $x \in [q,Q]$ satisfies these conditions, we have that $\int_{q}^{Q}(x-q)\,dF^{+}(x) \geq \int_{q}^{Q}(x-q)\,dF^{-}(x)$. In other words, $F^{-}(x)$ second-order stochastically dominates $F^{+}(x)$.

If s is small, the parameters of the model are in the region of case (i) of Proposition 2. In this region, the researcher is indifferent to the two distributions. If s is high enough, the parameters are in the region of case (ii). Given $F^{-}(q)$, the threshold quality q^{-o} is defined as:

$$s\left(\mu q^{-o} - A\right) - \delta s\mu\int_{q^{-o}}^{Q}\left(x - q^{-o}\right)dF^{-}(x) = \alpha\overline{q}.$$

Since $F^{+}(.)$ is a mean preserving spread of $F^{-}(.)$, we have that

$$s\left(\mu q^{-o}-A\right)-\delta s\mu\int_{q^{-o}}^{Q}\left(x-q^{-o}\right)dF^{+}(x)<\alpha\overline{q}.$$

Given that the derivative of the left hand with respect to q_1^o is positive and that

$$s\left(\mu q^{+o}-A\right)-\delta s\mu\int_{q^{+o}}^{Q}\left(x-q^{+o}\right)dF^{+}(x)=\alpha\overline{q},$$

we have that $q^{+o}>q^{-o}$. As shown in the proof of the previous proposition, this implies that $V^{+}>V^{-}$ and therefore the researcher prefers the risky research project.

Proof of Proposition 5

To prove this result, suppose that there are two projects characterised by the parameters (α_1, A_1) and (α_2, A_2), with $A_1 > A_2$ and $\alpha_1 > \alpha_2$, but otherwise identical. Project 1 is more basic than project 2. According to Proposition 2, we can write the discounted present expected value for each project $i = 1, 2$ as

$$V_i(s)=\frac{1}{1-\delta}\left[s\left(\mu q_i^{\circ}(s)-A_i\right)\right],$$

where V_i and q_i° are functions of the share s. The researcher prefers the applied project (project 2) if and only if

$$q_1^{\circ}(s)-q_2^{\circ}(s)<\frac{A_1-A_2}{\mu}.$$

From Proposition 2 and Corollary 3, one can show that $\frac{\partial^2 q^o}{\partial s\partial\alpha}<0$ and $\frac{\partial^2 q^o}{\partial s\partial A}<0$. As a consequence, $q_1^{\circ}(s')-q_2^{\circ}(s')<q_1^{\circ}(s'')-q_2^{\circ}(s'')$ whenever $s'>s''$. This implies that the larger is the share s, the more a researcher is inclined to choose the applied project. Indeed, if he chooses project 2 when the share is s'', he will continue to prefer that project for the larger share s'. However, the increase in s can make the researcher switch from project 1 to project 2. The second part of the Proposition follows directly from Corollary 3.

Proof of Lemma 6

The organisation payoff B starting in a period in which research is done is equal to

$$B = \int_0^Q \left(\rho - \alpha^+\right) x dF(x) + \delta F(q^\circ) B + \delta(1-s) \int_{q^\circ}^Q (\mu x - A)\, dF(x) + [1 - F(q^\circ)]\, \delta^2 B,$$

where q° is defined in Proposition 2. Rearranging this expression we have

$$(1-\delta)\left(1 + \delta\left[1 - F(q^\circ)\right]\right) B = \left(\rho - \alpha^+\right) \overline{q} + \delta(1-s) \int_{q^\circ}^Q (\mu x - A)\, dF(x), \qquad (5)$$

and therefore,

$$B = \frac{(\rho - \alpha^+)\overline{q} + \delta(1-s) \int_{q^\circ}^Q (\mu x - A)\, dF(x)}{(1-\delta)\left(1 + \delta\left[1 - F(q^\circ)\right]\right)}.$$

Notice that if $q^\circ = Q$ then $B = \left(\rho - \alpha^+\right) \overline{q} / (1-\delta)$.

Proof of Proposition 8

Overview of the proof. We need to find the solution to the program

$$\max_{\alpha^+, s} B(\alpha^+, s)$$

$$\text{s.t.} \qquad \left(\alpha^o + \alpha^+\right) \overline{q} + \delta s \mu \int_{q^\circ}^Q (x - q^\circ)\, dF(x) \geq c \qquad (IE),$$

$$s^m \leq s \leq 1 \text{ and } \alpha^+ \geq 0 \text{ with } q^\circ \text{ defined by } TA.$$

To simplify the problem, we distinguish between the two parameter configurations identified in Lemma 7. This lemma shows that in case (i), when $c \leq \alpha^o \overline{q}$, the IE condition is satisfied for all contracts. We argue below that in case (i) the optimal contract, (α^{+*}, s^*), should also satisfy $\alpha^{+*} = 0$.

In case (ii), when $c > \alpha^o \overline{q}$, Lemma 7 shows that the optimal contract should have $s^* > s^m$ or $\alpha^{+*} > 0$ (or both), to induce the researcher to provide effort. Our strategy here is to first analyse the case where the IE condition is binding but the other restrictions are not (case ii.1). We show in the first place that finding the optimal contract here is equivalent to finding the optimal stopping rule. Then, we find the contract that implements the optimal stopping rule. This contract is shown to induce the stopping rule that maximises the social welfare, $B + V$. Indeed, if it is possible, the best strategy for the organisation is

to maximise the total surplus and to offer the scientist a contract that induces the efficient stopping rule and covers the cost of effort. In the parameter configurations in which this contract is feasible (i.e., when the constraints on α^+ and s are non-binding), this is the solution. In the rest of parameter configurations, we find the corner solutions that are optimal (cases ii.2 and ii.3).

Case (i) Suppose first that $c \leq \alpha^o \overline{q}$. Notice that in the cheapest contract possible, $\alpha^+ = 0$ and $s = s^m$, the researcher would choose $q^\circ = Q$. If the organisation does not choose $\alpha^+ = 0$ and $s = s^m$, it is because it prefers a stopping rule q° such that $q^\circ < Q$. That is, the organisation would only use a different contract if it wishes to lower the stopping rule. Then, it is not optimal to increase α^+ above zero because it would be more expensive than to use s alone. Therefore, we should have $\alpha^{+*} = 0$. The optimal share s^* is the one that maximises $B(0, s)$ subject to $s^m \leq s \leq 1$, with q° defined by TA.

Case (ii.1) As mentioned above, if $c > \alpha^o \overline{q}$, we have three cases. Let us first suppose that in addition to this, we have that the IE condition is binding but the other restrictions are not, i.e. $s \geq s^m$, $s \leq 1$ and $\alpha^+ \geq 0$ are non-binding.

Let us first rewrite the objective function, B. Adding and subtracting $\alpha^o \overline{q}$ in the numerator of B from Lemma 6 (ii), we have

$$B(\alpha^+, s) = \frac{(\rho + \alpha^o)\overline{q} + \delta \int_{q^\circ}^{Q} (\mu x - A)\, dF(x) - \left((\alpha^o + \alpha^+)\, \overline{q} + s\delta \int_{q^\circ}^{Q} (\mu x - A)\, dF(x) \right)}{(1 - \delta)\left(1 + \delta\left[1 - F(q^\circ)\right]\right)}.$$

On the other hand, from the definition of V in (2), and the IE condition written as $(1 - \delta)V = c$, we have that

$$c = \frac{(\alpha^o + \alpha^+)\, \overline{q} + s\delta \int_{q^\circ}^{Q} (\mu x - A)\, dF(x)}{\left(1 + \delta\left[1 - F(q^\circ)\right]\right)}.$$

Substituting this into B, we can rewrite B as

$$B(\alpha^+, s) = \frac{1}{(1 - \delta)} \left(\frac{(\rho + \alpha^o)\overline{q} + \delta \int_{q^\circ}^{Q} (\mu x - A)\, dF(x)}{\left(1 + \delta\left[1 - F(q^\circ)\right]\right)} - c \right). \tag{6}$$

Since s nor α^+ appear explicitly in (6), B depends on s and α^+ via q° only. Given that the other restrictions are non-binding, the organisation should maximise (6) with respect to q°. We denote the optimal q° and the associated s and α^+ as q^e, s^e and α^{+e}, respectively.

We are now ready to characterise the candidate solution. Suppose first that the *solution is interior*, i.e. $q^e < Q$. Then q^e makes the first derivative of (6) equal to zero, i.e. it satisfies

$$\frac{\delta F'(q^e)L(q^e)}{(1-\delta)\left(1+\delta\left[1-F(q^e)\right]\right)^2} = 0, \tag{7}$$

where $L(q)$ is defined as

$$L(q) \equiv (\rho+\alpha^o)\overline{q} + \delta\int_q^Q (\mu x - A)\, dF(x) - (\mu q - A)\left(1+\delta\left[1-F(q)\right]\right).$$

Given that all ideas have positive probability, i.e., $F'(q) > 0$ for all q, the first-order condition implies that $L(q^e) = 0$. From the definition of a q° that satisfies the TA constraint (and more precisely from (3)), we have that

$$L(q^e) = \left[(\rho+\alpha^o) - \frac{\alpha^o + \alpha^{+e}}{s^e}\right]\overline{q}.$$

Therefore, $L(q^e) = 0$ implies that

$$\alpha^{+e} = s^e(\rho+\alpha^o) - \alpha^o, \tag{8}$$

and from the IE condition we obtain that

$$s^e \equiv \frac{c}{(\rho+\alpha^o)\overline{q} + \delta\mu\int_{q^e}^Q (x-q^e)\, dF(x)},$$

and hence

$$\alpha^{+e} \equiv \frac{c(\rho+\alpha^o)}{(\rho+\alpha^o)\overline{q} + \delta\mu\int_{q^e}^Q (x-q^e)\, dF(x)} - \alpha^o.$$

In order to make sure that q^e is a maximum of B, we need to show that the second derivative of B at q^e is negative. From (7), the sign of the second derivative at q^e is equal to the sign of

$$\left[F''(q^e)L(q^e) + F'(q^e)L'(q^e)\right]\left(1+\delta\left[1-F(q^e)\right]\right) + 2\delta F'(q^e)F'(q^e)L(q^e),$$

and given that $L(q^e) = 0$ this is equal to

$$F'(q^e)L'(q^e)\left(1+\delta\left[1-F(q^e)\right]\right).$$

Therefore the sign is equivalent to the sign of $L'(q^e)$, which is equal to

$$-\mu\left(1+\delta\left[1-F(q^e)\right]\right) < 0.$$

Suppose, second, that the *solution is not interior*, i.e. the optimal stopping rule never induces commercialisation, $q^e = Q$. Then, given that the IE constraint is binding, we have $\alpha^{+e} \equiv \frac{c}{\overline{q}} - \alpha^o$. The optimal share should be such that no commercialisation is induced, i.e. $s^e = s^m$.

We are now going to gain some intution about the solution candidate. Substitute α^{+e} defined in (8), into TA. As a result, we have

$$(\mu q^\circ - A) = (\rho + \alpha^o)\overline{q} + \delta\mu \int_{q^\circ}^{Q} (x - q^\circ)\, dF(x).$$

This shows that the optimal contract, which specifies α^{+e}, induces the stopping rule q^o that would be chosen to maximise the sum of the researcher's and organisation's profits, $(B + V)$. That is, s^e, α^{+e} and the resulting q^e maximise total welfare and satisfy IE with equality.

Finally, this candidate solution is indeed a solution if and only if $s^e \leq 1$, $\alpha^{+e} \geq 0$, which is the case when

$$c \leq (\rho + \alpha^o)\overline{q} + \delta\mu \int_{q^e}^{Q} (x - q^e)\, dF(x) \quad \text{and} \quad c \geq \alpha^o \overline{q} + \frac{\alpha^o \delta\mu \int_{q^e}^{Q} (x - q^e)\, dF(x)}{(\rho + \alpha^o)}. \tag{9}$$

Case (ii.2) Assume that $c > (\rho + \alpha^o)\overline{q} + \delta\mu \int_{q^e}^{Q} (x - q^e)\, dF(x)$, i.e., the share that would be needed to implement the efficient stopping rule is such that $s^e > 1$. For $s = 1$, the IE condition defines

$$\alpha^c \equiv \frac{c - \delta\mu \int_{q^\circ}^{Q} (x - q^\circ)\, dF(x)}{\overline{q}} - \alpha^o.$$

Note that $\alpha^c \geq 0$, since $c \geq \alpha^o \overline{q} + \delta\mu \int_{q^o}^{Q} (x - q^o)\, dF(x)$ is implied by $c > (\rho + \alpha^o)\overline{q} + \delta\mu \int_{q^e}^{Q} (x - q^e)\, dF(x)$ and $q^\circ > q^e$.

The optimal contract in this case is given by $s^* = 1$ and $\alpha^{+*} = \alpha^c$. Indeed, the optimal contract cannot be below the IE constraint because it would not induce effort. It cannot be strictly above, $\alpha^{+*} > \alpha^c$, either. This is because the IE constraint would then be non-binding and from Corollary 3 we know that it is possible to keep q° constant by decreasing s and α^+, increasing the profits of the organisation.

Case (ii.3) Assume $c \leq (\rho + \alpha^o)\overline{q} + \delta\mu \int_{q^e}^{Q} (x - q^e)\, dF(x)$ and $c < \alpha^o \overline{q} + \frac{\alpha^o \delta\mu \int_{q^e}^{Q} (x - q^e) dF(x)}{(\rho + \alpha^o)}$ i.e., the commercial incentive required to implement the efficient stopping rule is feasible,

$s^e \leq 1$, but the scientific incentive is not, $\alpha^{+e} < 0$. Then the optimal contract is in a corner solution with $\alpha^{+*} = 0$. If $\alpha^{+*} = 0$, the IE condition can be rewritten as

$$s \geq s^c \equiv \frac{c - \alpha^o \overline{q}}{\delta\mu \int_{q^o}^{Q} (x - q^o)\, dF(x)}.$$

Then the optimal share s^* is the one that maximises $B(0, s)$ subject to $s^c \leq s \leq 1$, with q° defined by TA.

Proof of Corollary 9

The proof proceeds in three steps. In the first, in the uniform case, we show that as we increase α^o the relevant regions in Proposition 8 are successively the ones in cases (ii.2), (ii.1), (ii.3) and (i). In the second step we argue that, although in case (ii.2) the optimal share s^* is constant and equal to 1, it is decreasing as a function of α^o in case (ii.1). In the third step, we show that in case (i), the optimal share is increasing in α^o, at least for $\rho < \overline{\rho}(\alpha^o)$ and $A = 0$.

Step 1: ordering of cut-offs. Clearly, if $\alpha^o > 2c$, we are in case (i). If, instead, $\alpha^o < 2c$, we are in cases (ii.1), (ii.2) or (ii.3) depending on the cut-offs defined in (9).

It is easy to show that both $m(\alpha^o)$ and $n(\alpha^o)$, defined as

$$m(\alpha^o) \equiv (\rho + \alpha^o) + \delta\mu\,(1 - q^e)^2 \text{ and } n(\alpha^o) \equiv \alpha^o + \frac{\alpha^o \delta\mu\,(1 - q^e)^2}{(\rho + \alpha^o)},$$

where

$$1 - q^e = \frac{1}{\delta\mu}\sqrt{\mu^2 - \mu\delta\,(\rho + \alpha^o - 2\,(\mu - A))} - \mu,$$

are increasing in α^o and that $m(\alpha^o) \geq n(\alpha^o)$ for any α^o. Then, from (9), case (ii.1) in the uniform case is defined for $\underline{\alpha}^o < \alpha^o < \overline{\alpha}^o$, where $\underline{\alpha}^o$ and $\overline{\alpha}^o$ are defined as $m(\underline{\alpha}^o) = 2c$ and $n(\overline{\alpha}^o) = 2c$. Clearly, if $\alpha^o < \underline{\alpha}^o$ we are in case (ii.2) and if $\overline{\alpha}^o < \alpha^o < 2c$, we are in case (ii.3).

Step 2: s^* decreasing as a function of α^o for $\underline{\alpha}^o < \alpha^o < \overline{\alpha}^o$. Here, we are in case (ii.1) of Proposition 8 and q^e solves $L(q) = 0$, where in the case of a uniform distribution $L(q)$ can be simplified to

$$L(q) = \frac{1}{2}(\rho + \alpha^o) + \frac{1}{2}\mu\delta\,(1 - q)^2 - (\mu q - A),$$

and solving,

$$q^e = \frac{1+\delta}{\delta} - \frac{1}{\delta}\sqrt{\frac{\mu - \delta\left(\rho + \alpha^o - 2\left(\mu - A\right)\right)}{\mu}}.$$

If q^e is the solution to the problem, the optimal share is given by s^e, where in this case,

$$s^e = \frac{c}{(\rho+\alpha^o)\frac{1}{2} + \delta\mu\frac{1}{2}\left(1-q^e\right)^2}.$$

Notice that

$$sign\left(\frac{\partial s^e}{\partial \alpha^o}\right) = -sign\frac{\partial\left((\rho+\alpha^o)\frac{1}{2} + \delta\mu\frac{1}{2}\left(1-q^e\right)^2\right)}{\partial\alpha^o}$$

and, substituting q^e and s^e, and simplifying,

$$\frac{\partial\left((\rho+\alpha^o)\frac{1}{2} + \delta\mu\frac{1}{2}\left(1-q^e\right)^2\right)}{\partial\alpha^o} = \frac{1}{2} - \delta\mu\left(1-q^e\right)\frac{\partial q^e}{\partial\alpha^o} = \frac{\mu}{\sqrt{\mu^2 - \mu\delta\left(\rho+\alpha^o-2\left(\mu-A\right)\right)}} > 0,$$

Hence s^e is decreasing in α^o.

Step 3: s^* increasing as a function of α^o for $\alpha^o > 2c$. Here we are in case (i) of Proposition 8. As shown in the proposition, IE is never binding and $\alpha^+ = 0$. Given that $A = 0$, s^* solves

$$\max_s \frac{\rho + (1-s)\delta\mu\left(1-q^{\circ 2}\right)}{2\left(1-\delta\right)\left(1+\delta\left(1-q^\circ\right)\right)}$$

$$\text{s.t.} \qquad s \geq \frac{\alpha^o}{2\mu},\ s \leq 1, \text{ and } \ q^o = \frac{(1+\delta)}{\delta} - \frac{1}{\delta}\sqrt{\frac{s\mu(1+2\delta) - \delta\alpha^o}{s\mu}}.$$

Assuming an interior solution, the first-order condition is given by

$$\frac{-\delta\mu\left(1-q^{\circ 2}\right)\left(1+\delta(1-q^\circ)\right) + \delta(\rho + (1-s)\mu P(q^\circ))\frac{\partial q^\circ}{\partial s}}{2\left(1-\delta\right)\left(1+\delta(1-q^\circ)\right)^2} = 0,$$

where

$$P(q) \equiv \delta\left(1-q^2\right) - 2q\left(1+\delta\left(1-q\right)\right).$$

By the implicit function theorem, and given that the derivative of the first-order condition with respect to s is negative (because it is a maximum), we have that $\frac{\partial s^*}{\partial \alpha^o}$ shares the same sign as the derivative of the first-order condition with respect to α^o. The numerator of such derivative (divided by δ) is given by

$$\mu\left[2q^\circ + \delta(1-q^\circ)\left(1+3q^\circ\right)\right]\frac{\partial q^\circ}{\partial\alpha^o} + (\rho + (1-s)\mu P)\frac{\partial^2 q^\circ}{\partial s\partial\alpha^o} - 2(1-s)\mu\left(1+\delta\left(1-q^\circ\right)\right)\frac{\partial q^\circ}{\partial s}\frac{\partial q^\circ}{\partial\alpha^o}.$$

It is easy to show that $\frac{\partial q^{\circ}}{\partial s} < 0$, $\frac{\partial q^{\circ}}{\partial \alpha^o} > 0$ and $\frac{\partial^2 q^{\circ}}{\partial s \partial \alpha^o} < 0$. Then, it is sufficient to show that $\rho + (1-s)\mu P < 0$. First notice that

$$\frac{\partial P(q)}{\partial q} = -2\delta q - 2 - 2\delta\,(1-2q) = -2 - 2\delta\,(1-q) < 0,$$

and $P(\hat{q}) = 0$ where

$$\hat{q} \equiv \frac{(1+\delta)}{\delta} - \frac{1}{\delta}\sqrt{1+2\delta} < \frac{(1+\delta)}{\delta} - \frac{1}{\delta}\sqrt{\frac{1}{s}\left(s + 2s\delta - \delta\alpha^o\right)} = q^o.$$

Therefore, $P(q^o) < P(\hat{q}) = 0$. Hence, we have that for $\rho < \overline{\rho}(\alpha^o)$, $\frac{\partial s^*}{\partial \alpha^o} > 0$.

Proof of Proposition 10

At $t = 1$ the researcher does research and at the end of the period obtains q_1 and A_1. He has to decide whether to do research or development during $t = 2$. If he chooses to look for a new idea, at the end of the second period he obtains, q_2 and A_2 and a payoff of $\alpha_2 q_2$. At this point, he would have to decide whether to do research again at $t = 3$, obtaining $\alpha_3 q_3$ at the end of the period, or to commercialise, obtaining $s_3(\mu q_2 - A_2)$. If instead he decides to do development at $t = 2$ he obtains $s_2(\mu q_1 - A_1)$ at the end of the second and $\alpha_{3'} q_{3'}$ at the end of $t = 3$. In summary the *ex-post* payoffs are if he chooses to do research in the second and the third,

$$\alpha_1 q_1 + \delta\alpha_2 q_2 + \delta^2 \alpha_3 q_3,$$

if, instead he decides to do research in the second and development in the third, he obtains

$$\alpha_1 q_1 + \delta\alpha_2 q_2 + \delta^2 s_3(\mu q_2 - A_2),$$

and finally, if he decides to commercialise in the second (and therefore do research in the third), he obtains

$$\alpha_1 q_1 + \delta s_2(\mu q_1 - A_1) + \delta^2 \alpha_{3'} \overline{q}_{3'}.$$

Solving the game by backward induction, the researcher will decide to develop in the last period if and only if

$$s_3(q_2 + a_2) \geq \alpha_{3'} \overline{q}_{3'}. \tag{10}$$

Define for every q_2 the level $\widehat{A}_2(q_2)$ as the one that satisfies $s_2\left(\mu q_2 - \widehat{A}_2(q_2)\right) = \alpha\overline{q}_{3'}$, with $\widehat{A}_2(q_2)$ increasing in q_2. Going backwards, he will develop in the second period if and only if

$$s_2(\mu q_1 - A_1) \geq \alpha_2\overline{q}_2 - \delta\alpha_{3'}\overline{q}_{3'} + \delta\int_0^{\overline{Q}}\int_{\underline{A}_2}^{\widehat{A}_2(x)} s_3(\mu x - y)dH_2(y)dG_2(x) + \delta\alpha_3 q_3\int_0^{\overline{Q}}(1 - H_2(\widehat{A}_2(x))dG_2(x).$$

Proof of Corollary 11

In the stationary environment, the stopping rule after the second period of research is

$$s(\mu q_2 - A_2) = \alpha\overline{q}, \tag{11}$$

and when distributions are stationary, then we can rearrange the terms of the first period stopping rule as

$$s(\mu q_1 - A_1) = \alpha\overline{q} + \delta\int_0^{Q}\int_{\underline{A}_2}^{\widehat{A}_2(x)} \left[s(\mu x - y) - \alpha\overline{q}\right] dH(y)dG(x). \tag{12}$$

Since by definition the function in the integral is positive in that domain, we have that the left-hand side is higher in (12) than in (11) and, therefore, the researcher is less likely to develop (for the same realised q and A) in the second period than in the third.

Proof of Proposition 12

If $A_i \equiv 0$ and $\mu = 1$ we have that the stopping rule in the first and second periods is defined by q_1^o and q_2^o, where

$$s_2 q_1^o + \delta\alpha_3\bar{q}_3 = \alpha_2\overline{q}_2 + \delta s_3\int_{q_2^o}^{\overline{Q}}(x - q_2^o)dG_2(x) + \delta\alpha_{3'}\overline{q_{3'}} \text{ and } q_2^o = \frac{\alpha_{3'}\overline{q}_{3'}}{s_3}$$

and

$$V = \alpha_1\overline{q}_1 + \delta s_2 q_1^o + \delta^2\alpha_3\bar{q}_3 + \delta s_2\int_{q_1^o}^{\overline{Q}}(x - q_1^o)dG_1(x). \tag{14}$$

A mean preserving spread of $\widetilde{q}_1$ implies an increase in the integral term of V and has no effect on q_2^o and q_1^o. Hence, it increases V. A mean preserving spread of $\widetilde{q}_2$, increases the integral in the first period time allocation. As a result q_1^o increases and given that

$$\frac{\partial V}{\partial q_1^o} = \delta G_1(q_1^o)s_2\mu > 0,$$

we have that it also increases V. This completes the first part of the proof.

Let us denote $G_i^+(q)$ and $G_i^-(q)$ two distribution functions, in which the first is a mean preserving spread of the second. In this case we have that $V\left(G_1^+\right) - V\left(G_1^-\right)$ is equal to

$$\delta s_2 \int_{q_1^o\left(G_1^+\right)}^{\overline{Q}} (x - q_1^o\left(G_1^+\right))dG_1^+(x) - \delta s_2 \int_{q_1^o\left(G_1^-\right)}^{\overline{Q}} (x - q_1^o\left(G_1^-\right))dG_1^-(x),$$

and $V\left(G_2^+\right) - V\left(G_2^-\right)$ equal to

$$\delta s_2 \left(q_1^o\left(G_2^+\right) + \int_{q_1^o\left(G_2^+\right)}^{\overline{Q}} (x - q_1^o\left(G_2^+\right))dG_1(x) - q_1^o\left(G_2^-\right) - \int_{q_1^o\left(G_2^-\right)}^{\overline{Q}} (x - q_1^o\left(G_2^-\right))dG_1(x) \right).$$

Suppose that we take a mean preserving spread of $G_1(q)$. In this case $q_1^o\left(G_1^+\right) = q_1^o\left(G_1^-\right)$. An increase in s_2 increases the incentives to take more risk, given that

$$\frac{\partial\left[V\left(G_1^+\right) - V\left(G_1^-\right)\right]}{\partial s_2} = \delta\left[\int_0^{q_1^o} x dG_1^-(x) - \int_0^{q_1^o} x dG_1^+(x)\right] > 0.$$

But, if we increase s_3 we have that

$$\frac{\partial\left[V\left(G_1^+\right) - V\left(G_1^-\right)\right]}{\partial s_3} = \delta^2\left[G_1^+(q_1^o) - G_1^-(q_1^o)\right]\int_{q_2^o}^{\overline{Q}} (x - q_2^o)dG_2(x),$$

whose sign coincides with the sign of $G_1^+(q_1^o) - G_1^-(q_1^o)$. Given that one is a mean preserving spread of the other we have that $G_1^+(q_1^o) - G_1^-(q_1^o) > 0$ if and only if $q_1^o > \bar{q}_1$.

Suppose now that we take a mean preserving spread of $G_2(q)$. In this case $q_1^o\left(G_2^+\right) > q_1^o\left(G_2^-\right)$. Simplifying, we have that an increase in s_2, decreases $V\left(G_2^+\right) - V\left(G_2^-\right)$. Indeed, simplifying, we have that

$$\frac{\partial\left[V\left(G_2^+\right) - V\left(G_2^-\right)\right]}{\partial s_2} = \delta\int_{q_1^o\left(G_2^+\right)}^{\overline{Q}} x dG_1(x) - \delta\int_{q_1^o\left(G_2^-\right)}^{\overline{Q}} x dG_1(x) < 0,$$

whereas the derivative of $V\left(G_2^+\right) - V\left(G_2^-\right)$ with respect to s_3 is equal to

$$\delta^2 G_1(q_1^o\left(G_2^+\right))\int_{q_2^o}^{\overline{Q}} (x - q_2^o)dG_2^+(x) - \delta^2 G_1(q_1^o\left(G_2^-\right))\int_{q_2^o}^{\overline{Q}} (x - q_2^o)dG_2^-(x)$$

and this is greater than 0 because $q_1^o\left(G_2^+\right) > q_1^o\left(G_2^-\right)$.

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