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Commercial Incentives in R&D: Research versus Development*

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Abstract

This paper proposes a framework to analyse the effects of scientific rewards and commercial incentives on the pattern of research. We build a simple repeated model of a researcher capable to obtain innovative ideas. We analyse how scientific and commercial incentives affect the allocation of the researcher's time between research and development. Although commercialisation incentives reduce the time spent in research, they might also affect the choice of research projects. Monetary 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 optimal incentive scheme for a given project in terms of the researcher's and the organisation's objectives.

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1 Introduction

The industrial base of advanced economies relies heavily on research and development (R&D). Scientific and technological innovation creates competitiveness, sustainable economic growth and welfare. The prominent role of universities and R&D intensive firms as key providers of scientific knowledge implies that any change in the research environment is (and should be) widely debated.

The introduction of the Bayh-Dole act, which gave American universities the right to own and license inventions emanating from federally funded research, coincided with a dramatic increase in the number of university patents, licensing agreements and revenues.[1] Many people have seen this surge as a great benefit to society. Others, however, have expressed concerns about the possibility that commercial rewards might be affecting the choice of research projects, "skewing" research from basic towards more applied (Florida and Cohen, 1999).[2] Still, many directors of technology transfer offices believe that many inventions with commercial potential are not disclosed to their offices (Jensen et al., 2003). Faculty involvement in development is necessary for commercial success (Jensen and Thursby, 2001) and researchers might not want to take time away from research.

Even if they have always had a clearer commercialisation objective, research-intensive firms also face the problem of providing adequate incentives for both research and development. The long-run level of research productivity in pharmaceutical drug discovery,

[1] The 86 universities responding to the Association of University Technology Managers survey in 1991 and 1998, for example, reported an increase in patent applications of 176 percent and licenses executed of 131 percent (Jensen et al., 2003). In recent years, in a large number of EU countries an increase in patenting has also been closely following the transfer of ownership of patents to universities (Geuna and Nesta, 2006).

[2] After the costs are recovered, the royalty income is divided between the university's transfer office, the faculty members listed as inventors and their departments. In many of these agreements the faculty can receive as much as 50% of the total royalty revenue. Lach and Schankerman (2008) provide strong empirical support for the importance of inventor's royalty shares for university performance in terms of inventions and license income. Survey results by Blumenthal et al. (1986) also indicate that faculty members whose research is supported by the industry are four times more likely than faculty without such support to report that their choices of research topics have been affected by the chance that the results would have commercial application.

for example, depends on the effort devoted towards the solution of fundamental scientific problems and the development of potentially marketable drugs (Cockburn et al., 1999). In the late 1970s, the pharmaceutical industry experienced a significant exogenous shock to the technology of drug discovery which induced firms to provide high-powered incentives for research, based on scientific publications. More recently, R&D managers of large research-intensive firms have claimed that they are facing, as universities, greater pressures to "sell" R&D services to their customers (Zettelmeyer and Hauser, 1995).

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 to obtain innovative ideas. In each period, the researcher might decide to undertake new research, generating thus a new idea. 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").[3] Alternatively, she may decide to develop prior research into a commercially valuable innovation. If she does so, however, the researcher forgoes the opportunity of undertaking new research and therefore of receiving a new idea in that period.

We analyse, in the first place, how scientific and market incentives affect the allocation of 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 affect 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 high-quality path-breaking (ex-post) ideas, which are more likely to be generated through (ex-ante) riskier research programs. Although

[3]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 both 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.

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, "the line between basic scientific research and applied scientific research is hard to draw. There is a continuous spectrum of scientific activity. 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 Zettelmeyer and Hauser (1995), managers of R&D firms also think that basic research is the most uncertain one.

We also address the problem of providing incentives for research workers. We characterise the optimal incentive scheme as a function of the employee and the employer's characteristics. Researchers are not only driven by monetary rewards but also by peer recognition and the "puzzle" joy (Stephan and Levin, 1992). Although universities and research-intensive firms have different objectives, both of them can now use commercial and scientific incentives to motivate their researchers and to induce them 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 that have very strong and for those that have very weak intrinsic preferences for research. For those with strong preferences, the organisation needs to induce development while for those with weak intrinsic preferences for research the organisation needs to provide incentives to work. As a consequence, even for non-scientific oriented organisations, it can be optimal to hire an intermediate scientific-oriented researcher. Similarly, it might be optimal to prohibit or limit publications of researchers with strong intrinsic preferences for research.

To the best of our knowledge, this is the first paper that characterises the optimal provision of commercial and scientific incentives. We believe that this is also the first analysis of the impact of the introduction of commercial incentives on the choice of research projects in academia.[4] Lacetera (2006) compares the incentives of academic and industrial

[4]It is important to note that we are concentrating on early-stage research. Aghion et al. (2005), 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.

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 perform more research into the project. Rather, she faces the trade-off between commercialising the *current* idea and dropping it and venturing into a *new* research project of uncertain quality.[5] In this sense, ours is complementary to his paper. He finds that a greater focus on commercialisation can lead to additional research into the projects and we find that the introduction of commercialisation can lead to more intensive research for ex-post path-breaking innovations. Thursby et al. (2005) 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 effort are complementary.

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, she spends her time either doing research or being involved in further development of prior knowledge. If she pursues research she obtains, at the end of the period, an "idea" of random quality q, drawn from an independent and identical distribution $F(q)$ with density $f(q)$, expected value $\overline{q}$ and support $[0, Q]$. As stressed by this formulation, the outcome of any research project is inherently uncertain.

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

In line with the recent literature in the economics of science (Murray and Stern, 2007), the research output has both scientific value and potential market value. The scientific content is publishable in a scientific journal and it does not jeopardise further patent rights.[6] 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 in addition to tenure, peer recognition concerns and 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, she 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 in doing consultancy, in being involved in a spin-off or in spending time in any activity related to the scientific output that would allow her 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 $\mu q - A$.[7] 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 at this early stage of development. This cost should be net of any commercial value which is

[6] We discuss at the end of Section 3 what happens if academic 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).

[7] We assume 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). We also assume in the basic setup that the applicability factors μ and A are certain. It would be equivalent to assume that they are random, with independently distributributions whose realisations are not observed until the end of the development period. In Section 4 we discuss the case in which the researcher observes μ at the end of the research period. In Section 6 we analyse the case in which A is observed at the end of the research period.

independent from the quality of the idea, which would be subtracted from A.[8] We assume that the commercial value is an increasing function of the quality of the ideas (i.e. $\mu > 0$) and that the ideas of the lowest quality do not have commercial value (i.e. $A > 0$), while the ones of the highest quality do have commercial value ($\mu Q > A$).

When selling the innovation the researcher receives a share s ($\in (0,1)$) of the commercial benefits of the innovation.[9] 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.[10]

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 any commercial value. By being involved in development, however, the researcher forgoes the opportunity of undertaking new research and receiving 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"). Moreover, 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 ($\in (0,1)$).[11] An 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

[8] In the paper we assume that these additive benefits do not outweight the costs to avoid the possibility that the worst commercial ideas are developed. Relaxing this assumption, though, would only create an extra case in Proposition 2 below.

[9] If the development period consists in being involved 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. This is consistent with the contracts used for university spin-offs (see for example, Macho-Stadler et al., 2007).

[10] As explained in Beath et al. (2003), Karl Compton, president of the MIT between 1930 and 1948, was concerned about the damage of consultancy on the MIT's reputation and research. He decided to regulate the amount of consulting by taxing consultancy income at a rate of 50%.

[11] An infinite horizon setups is indeed appropriate if after each period the researcher believes that the model will continue for an additional period with some probability.

a first step, at studying the simplest situation where the researchers are confronted with the research versus development decision. In Section 6, we consider a finite version of our basic model, which allows us to study deadline effects (as 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 she 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 cutoff 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 her best ideas while

dropping the worse ones (case ii). The quality in 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 she never develops) shrinks and/or when the threshold within the region of case (ii) (in which she might develop) 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, induce more development. Indeed, the empirical results by Thursby and Thursby (2007) confirm that the probability that a researcher discloses 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, they 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 researcher (with a high δ) should be more reluctant to develop a given idea. Although she might end up developing more or less in total, the commercial value of her average innovation should definitely be higher.

Also intuitively, 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 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. As we shall see in this section, whether the researcher would choose more basic or more applied projects hinges crucially on how basicness is defined. As argued in the introduction one of the potential differences between basic and applied projects is that basic projects are riskier than applied projects (Nelson, 1959). But, another potential difference is that the outcomes of basic projects might, in expected terms, be more difficult to commercialise and carry higher scientific reward. We should consider each of these two distinctions in turn.[12]

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 will be more willing to choose projects that are more basic in nature when they 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 her 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.*

[12] Other distinctions 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.

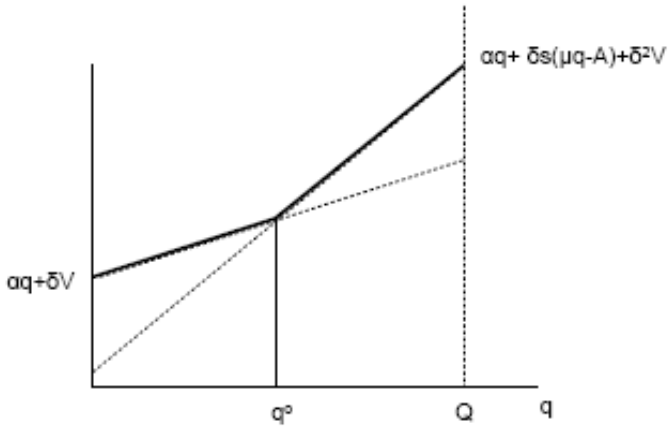

Figure 1: Researcher's utility in a given period (for a given V) as a function of the quality of the idea.

The intuition behind the preference for the risky project follows from the fact that the researcher acts as if she was risk-loving with respect to the quality of the output. As we can see in Figure 1, 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 doing 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 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 therefore they are 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 induce the researcher to select between two increasing

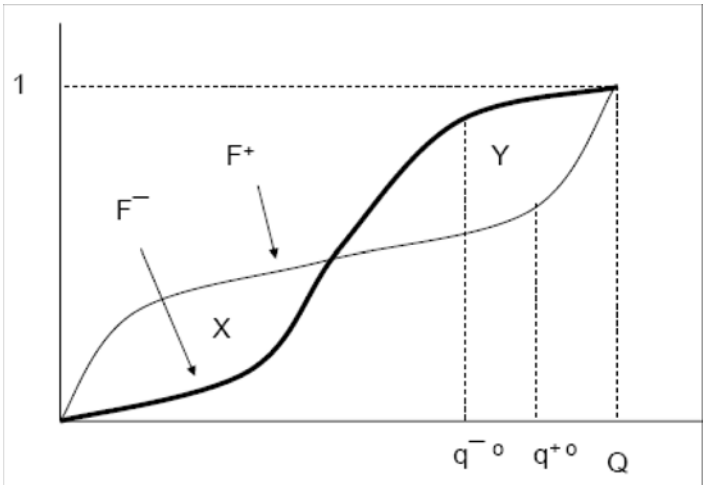

Figure 2: Distribution $F^{-}(\cdot)$ and a mean preserving spread, $F^{+}(\cdot)$ (Area X=Area Y).

functions. Assume that the commercial value of an idea of quality q is $\mu(q)q$. Given that the best innovations have 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 rewards from technology transfer. Further, the fact that the researcher selects riskier projects than with no commercial rewards should hold if the value of publications has the form $\alpha(q)q$ for any $\alpha(q)$ and not only when $\alpha(q)$ is constant. Indeed, although she might not always act as if she was risk-loving she 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 or, in other words, the net costs A of turning the innovation into a commercial product are lower. Also, 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 high scientific value, commercial rewards might induce a shift towards more applied or more basic. 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 large. All in all, the introduction of commercial incentives should not necessarily "skew" research towards more applied projects.[13]

4.3 Extensions

Our basic model assumes that the development factor is certain. But, as mentioned in Footnote 7, 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.[14] Both are equivalent given that only the expectation (and not the realisation) is relevant for the time allocation decision. It might be, however, that the researcher realises the commercial value of a piece of knowledge at the end of the research period, when she also realises its quality. Then, as shown formally in Banal-Estañol and Macho-Stadler (2007), the ideas that have turned out to have high commercial value are more likely to be developed. But, still, the introduction of remuneration induces researchers to choose riskier projects in terms of quality. Furthermore, researchers would also tend 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

[13] An important consideration for social welfare, which is beyond the reach of our model, is whether several researchers will 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.

[14] 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 choose between two projects, one of which is a mean-preserving spread of the other.

have been subject of a patent application might be delayed (Geuna and Nesta, 2006). Suppose that if the researcher develops, then she 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 we also show 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 to ensure that they allocate an "optimal" amount of time to research and development. In this section, we analyse the optimal incentive scheme of an organisation that can use commercial and scientific incentives. We assume that the researcher works in a predetermined pool of projects and thus abstract from the project selection dimension. In contrast, we extend our analysis to allow for the possibility that, in addition to the time allocation decision, the researcher has the possibility of not exerting any effort.

Notice first that research organisations differ, to a great extent, as to which 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 universities' preferences might also differ, depending on their field of specialisation and on the institutional environment.[15] 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.[16] Higher values of ρ imply a higher concern for scientific reputation or prestige from successful research and a lower importance of commercial profits.

Suppose that the organisation pays the researcher through a contract (s, α^+), where s is her share of the commercial revenues and α^+ is a prize (in monetary terms) awarded

[15] The Bayh-Dole Act has pushed some universities to encourage technology licensing and commercial arrangements and to include them in their strategic plans (e.g., Iowa University).

[16] We are omitting the uninteresting case in which the organisation only cares about publications.

to the quality of the research, in addition to her intrinsic puzzle joy or peer recognition, α^o.[17] That is, we decompose the marginal benefit of the quality of the publications as $\alpha = \alpha^+ + \alpha^o$. As a result, a given researcher's α depends on the organisation she works for. As we did for the researcher, 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 *The discounted present expected value B for the organisation is*

$$\begin{aligned} &(i) \quad B(\alpha^+, s) = \frac{\rho - \alpha^+}{1-\delta}\overline{q} \qquad \text{if } q^\circ = Q, \\ &(ii) \quad B(\alpha^+, s) = \frac{(1-s)}{s}V + \frac{s(\rho+\alpha^o) - (\alpha^+ + \alpha^o)}{s\,(1-\delta)\,(1+\delta\,[1-F(q^\circ)])}\overline{q} \qquad \text{if } q^\circ < Q, \end{aligned}$$

where q° and V are defined in Proposition 2.

Suppose also that in each period if the researcher works, either in research or development, she incurs a cost c. But she can also not perform any activity at a 0 cost. If she is in a research period she devotes effort, assuming she will also do so in the future, if and only if her expected utility from working, $V - c$, is greater than her expected utility from shirking, $0 + \delta V$. 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 both 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, 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

[17] Note that in what follows we can ignore the researcher's participation constraint because it can be guaranteed through a fixed transfer, if necessary.

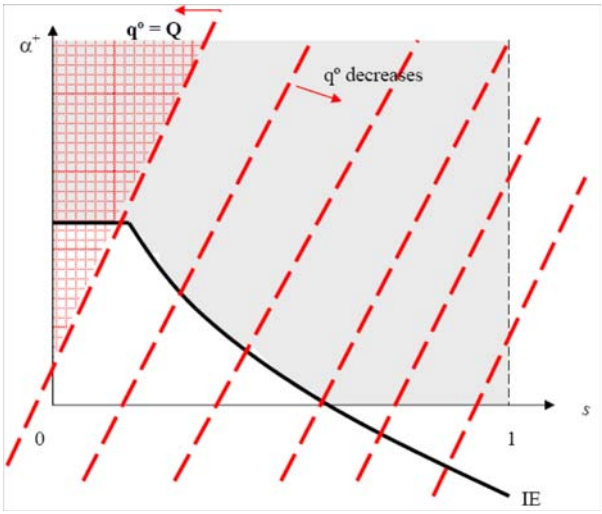

Figure 3: The isolevel dashed curves represent the time allocation constraint (TA) for a given q^o. The isolevel curve for $q^\circ = Q$ is the thick squared region. The shadowed area represents the contracts satisfying the incentive to provide effort constrant (IE).

increase s further, though. If $\alpha^+ \geq c/\overline{q} - \alpha^o$ the researcher would provide effort for any s, thanks to the scientific value of the publications. And, if $c/\overline{q} \leq \alpha^o$ she would provide effort for any s and α^+, thanks to the intrinsic value from scientific research.

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

$$\max_{s,\alpha^+} B(\alpha^+, s) \tag{1}$$
$$\text{s.t.} \qquad TA,\ IE,\ s \in [0,1] \text{ and } \alpha^+ \geq 0.$$

In order to present the solution of the problem, let us denote q^e the stopping rule that maximizes the total surplus, $B + V$. Further, define s^e and α^{+e} the contract that induce q^e and satisfy IE with equality (this pair might not be within the feasible bounds of α^+ and s). When the stopping rule induces the commercialisation of some ideas, $q^e < Q$, the contract (α^{+e}, s^e) is unique. However, when it generates no commercialisation, $q^e = Q$, (α^{+e}, s^e) is a set of contracts. If s^e is below a certain level no commercialisation occurs (see Proposition 2) and all the contracts are equivalent.

Proposition 7 *The optimal incentive scheme* (α^{+*}, s^*) *satisfies:*
(i) For $c \leq \alpha^o \overline{q}$ *then,* $\alpha^{+*} = 0$ *and* $0 \leq s^* \leq 1$.
(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 $\alpha^c \equiv (c - \delta\mu \int_{q^\circ}^{Q} (x - q^\circ)\, dF(x))/\overline{q} - \alpha^o$ *and* $s^c \equiv (c - \alpha^o \overline{q}) / (\delta\mu \int_{q^o}^{Q} (x - q^o)\, dF(x))$.

Figure 3 helps to understand the results in Proposition 7. An organisation can obtain the same revenue at a lower cost by decreasing s and α^+ simultaneously while keeping 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 IE and therefore IE is never binding. 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 interested in inducing research only, the optimal contract has zero shares for the researcher. But if the organisation is also interested in inducing development then the optimal contract will include positive shares for the researcher to induce her to commercialise sometimes.

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 (in the sense that $\alpha^{+e} < 0$ or $s^e \notin [0, 1]$), 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 her no extra scientific incentives (case ii.3). In the latter, the organisation will again choose the optimal s in order to maximise B given TA and $\alpha^+ = 0$.

In order to illustrate how the optimal incentive scheme changes with the parameters, we now present, in Table 1, a numerical example based 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 how the optimal contract, the organisation's profits and the stopping rule (rows 3 to 5) 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 7 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. 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). Interestingly, both types of organisation use a high level of commercialisation shares for high but also for 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.

As a consequence, 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 too much research-driven, though, can also lower profits.

If it were possible to lower α^o, via a prohibition of research related activities that offer exposure to other scientists, it might be optimal to do so. For example, a commercially oriented organisation ($\rho = 0$) increase profits by reducing the researchers' intrinsic interests to publish from $\alpha^o = 0.5$ until $\alpha^o = 0.2$ or $\alpha^o = 0$.[18]

[18]The organisation can in principle do this at no cost. We are not proposing to use a negative α^+ but

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 she is induced to not commercialise. Comparing the stopping rules, more commercial oriented institutions will intuitively induce a lower threshold, q°.[19] 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) any contract satisfies the incentive to exert effort constraint. The optimal contract corresponds to the case (i) of Proposition 7 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, she has to receive a prize for publications in order to have incentives to work. If there are not any other benefits from hiring the researcher (except those included in B), the organisation might be better off not hiring the researcher, given that $B^* < 0$.

6 Retirement Effects

In this section we consider a three-period version of our basic model, which allows us to study deadline effects (that would appear if for example the researcher is close to retirement). At the same time, it enables us to consider non stationary research and development outcomes. We allow also for the possibility that the net costs of development,

to make it more difficult for the researcher to enjoy pure research results.

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

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.[20]

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 her share of commercial revenues in period i as α_i and s_i, respectively.

In this model, the researcher needs to take a time allocation decision at most twice, after the first research outcome, (q_1, A_1), and if she decides to undertake research in the second period, after the second research outcome, (q_2, A_2).

Proposition 8 *The optimal decision of the researcher is not to develop research output whose quality and net costs of development are such that* $A_i > \widehat{A}_i(q_i)$ *where* $\widehat{A}_i(\cdot)$ *is implicitly defined as*

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

where $K(\widehat{A}_2(\cdot))$ *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 $\alpha_{3'}\overline{q}_{3'}$ enlarge the set of combinations of quality and net costs for which the researchers 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 9 *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 commercialise in the third period than in the second.*

[20] This takes into account innovations with high scientific value and high commercial value, or having high scientific value and low commercial value, and so on.

Indeed, in the last period the researcher develops more because she does not have the extra loss from losing a potentially good idea. In Corollary 3 (Section 3), we show in the infinite model that the development threshold decreases if the marginal utility of scientific publications decreases. Assuming that the marginal utility decreases with tenure and age, we can argue that this is consistent with the fact that disclosure increases with tenure and age, at least until the middle ages (Thursby and Thursby, 2007). This corollary confirms this intuition in a more direct way.

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 will affect the present expected value V. As we can see in Proposition 8, $G_2(q)$ affects the time allocation behavior 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 induce 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, increase.

Proposition 10 *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 result shows that the effects of the researcher's share of commercial profits on the incentives to take riskier projects in period 1 or 2 are not clear-cut. When the researcher chooses the same pool of ideas in both periods (a research profile in which she has to invest) 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 firm 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 that can choose between undertaking new research or developing prior research into a commercially valuable innovation. We show that the researcher should pursue a new research project unless the quality of the outcome has enough commercial prospects to compensate a delay in undertaking new research. 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 her discipline has greater applicability and if the marginal utility of academic 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 faculty "skews" 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. Using faculty-level data from six major universities, Thursby and Thursby (2007) find no systematic change in the proportion of publications in basic versus applied journals between 1983 and 1999.[21] 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 has 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 should be more reluctant to develop research of a low quality. Instead, they are more willing to continue undertaking research because they are more likely to obtain results of higher quality 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.

Even if it is not especially designed for, our paper could also constitute a first step towards understanding incentive provision to the broader group of "knowledge workers",

[21] Hicks and Hamilton (1999) also found that the percentage of basic research that was performed at American universities remained unchanged between 1981 and 1995.

such as computer programmers, engineers and technology managers, who are meant to create, distribute, and apply knowledge across the organisation. Managers claim that knowledge workers are the key source of growth in most organisations (see e.g., Martin and Mondoveanu, 2003). Despite their importance, little is known about how to provide incentives to knowledge workers.

The problem of providing scientists with incentives to commercialise is related to the problem of inducing knowledge workers to distribute their knowledge. 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 them. As for the case of researchers, not all knowledge workers are alike. Some are better motivated than others to perform certain tasks. Knowledge workers can be incentivised, on the one hand, with a traditional bonus related to the performance of the firm. But, on the other hand, it might also be possible to include rewards to the acquisition of knowledge and the creation of new ideas. Examples include better work environments and 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 she 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 she will be able to sell the innovation if she develops and therefore she 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 simplifying gives

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

On the other hand, $q^\circ(V)$ should be defined here as $(1-\delta)V = s\left[\mu q^\circ - A\right]$. Hence,

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

Simplifying we have that q° is implicitly defined by

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

Since $j'(q) = s\mu + \delta s\mu(1 - F(q)) > 0$, the cut-off q° 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 $x\epsilon\left[0, q\right]$ and $u(x) = x - q$ if $x\epsilon\left[q, Q\right]$ satisfies these conditions, we have that $\int_q^Q \left(x - q\right) dF^+(x) \geq \int_q^Q \left(x - q\right) dF^-(x)$. 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 between 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 researcher is more inclined to choose the applied project the larger is the share s. Indeed, if she chooses project 2 when the share is s'', she will keep preferring 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

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

Notice that if $q^\circ = Q$ then $B = (\rho - \alpha^+)\,\overline{q}/\,(1-\delta)$. Suppose now that $q^\circ < Q$. From Proposition 2 this can only happen if $s > 0$. From the proof of the same Proposition 2, we have that

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

Multiplying equation (2) by s and subtracting $(1-s)$ multiplied by equation (3), we obtain

$$(1-\delta)\left(1 + \delta\left[1 - F(q^\circ)\right]\right)(sB - (1-s)V) = s\left(\rho - \alpha^+\right)\overline{q} - (1-s)\alpha\overline{q},$$

and simplifying

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

Proof of Proposition 7

This contract associated to the efficient solution is defined by

$$\begin{aligned} s^e &\equiv \frac{c}{(\rho + \alpha^o)\overline{q} + \delta\mu \int_{q^e}^Q (x - q^e)\, dF(x)} \text{ and } \alpha^{+e} = s^e(\rho + \alpha^o) - \alpha^o \text{ when } q^e < Q, \\ s^e &\in \left[0, \frac{c}{\mu Q - A}\right] = \left[0, \frac{c}{(\rho + \alpha^o)\overline{q}}\right] \text{ and } \alpha^{+e} = \frac{c}{\overline{q}} - \alpha^o \text{ when } q^e = Q. \end{aligned}$$

Note that when the stopping rule that maximizes total welfare induces the commercialisation of some ideas, $q^e < Q$, there is a unique contract (α^{+e}, s^e). However, when the the stopping rule that maximizes total welfare induces no commercialisation of some ideas, $q^e = Q$, there is a family of contract (α^{+e}, s^e) where $s^e \in \left[0, \frac{c}{\mu Q - A}\right]$ because all this shares

induce no commercialisation (see Proposition 2), hence no income from commercialisation, and consequently all these shares are equivalent.

Consider now the programme

$$\max_{s,\alpha^+} B$$
$$\text{s.t.} \qquad IE,\ s \geq 0,\ s \leq 1 \text{ and } \alpha^+ \geq 0$$
$$\text{with} \qquad q^\circ \text{ defined by } TA.$$

We distinguish two cases.

CASE (i). When $c \leq \alpha^o \overline{q}$ the IE constraint is satisfied for any contract. The optimal contract in this case has always $\alpha^{+*} = 0$, and s is the one that maximizes B given TA. Hence, (using TA from Proposition 2),

$$\begin{aligned} \text{if } \frac{dB}{ds}\left(s = \frac{\alpha\overline{q}}{(\mu Q - A)}\right) &\leq 0 \text{ then } s^* = 0 \text{ and } q^\circ = Q \text{ and} \\ \text{if } \frac{dB}{ds}\left(s = \frac{\alpha\overline{q}}{(\mu Q - A)}\right) &> 0 \text{ then } 1 > s^* > 0 \text{ and } q^\circ < Q. \end{aligned}$$

CASE (ii). Let us consider now the situations where $c > \alpha^o \overline{q}$. There are three candidates:

• *Case (ii.1)*: Assume IE binding while $s \geq 0$, $s \leq 1$ and $\alpha^+ \geq 0$ are non-binding

If IE is binding then, substituting in B, we can rewrite B as

$$\frac{1}{(1-\delta)}\left(\frac{(\rho+\alpha^o)\overline{q} + \delta\int_{q^\circ}^{Q}(\mu x - A)\,dF(x)}{(1+\delta\left[1-F(q^\circ)\right])} - c\right). \tag{4}$$

Then B depends on (s, α^+) only via q°. The organisation chooses the optimal q°, which if it is an interior maximum, is equal to the point that makes the first derivative equal to zero, i.e.

$$\frac{F'(q^\circ)L(q^\circ)}{(1-\delta)\left(1+\delta\left[1-F(q^\circ)\right]\right)^2} = 0, \tag{5}$$

where $L(q^\circ)$ is defined as

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

where the last equality follows from the definition of $q^\circ(s, \alpha^+)$ in Proposition 2. Given that all points have positive probability, $F'(q^\circ) > 0$, we should have

$$\alpha^+ = s(\rho + \alpha^o) - \alpha^o. \tag{6}$$

Substituting this into the TA constraint, we have that

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

As a result, the induced q^{o} is chosen to maximise the sum of the researcher's and organisation's profits, $(B + V)$. We denote this level as q^{e}. Substituting q^{e} and (6) into IE we have

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

and therefore $\alpha^{+e} = s^{e}(\rho + \alpha^{o}) - \alpha^{o}$ if $q^{e} < Q$.

If the organisation chooses a corner solution for q° i.e., $q^{e} = Q$, then by Proposition 2, all shares $s^{e} \in \left[0, \frac{c}{\mu Q - A}\right] = \left[0, \frac{c}{(\rho+\alpha^{o})\overline{q}}\right]$ are equivalent and $\alpha^{+e} = \frac{c}{\overline{q}} - \alpha^{o}$. This covers the case in which $s = 0$ is binding.

It only remains to show that the second derivative is negative. The sign of the second derivative is equal to the sign of

$$\left[F''(q^{\circ})L(q^{\circ}) + F'(q^{\circ})L'(q^{\circ})\right](1 + \delta\left[1 - F(q^{\circ})\right]) + 2\delta F'(q^{\circ})F'(q^{\circ})L(q^{\circ})$$

given that at $q^{o} = q^{e}$ we have that $L(q^{e}) = 0$, this is equal to

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

and therefore the sign is equivalent to the sign of $L'(q^{\circ})$, which is equal to

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

This case is well defined if $s^{e} \leq 1$, $\alpha^{+e} \geq 0$.

• *Case (ii.2)*: Assume $c > (\rho + \alpha^{o})\overline{q} + \delta\mu \int_{q^{e}}^{Q} (x - q^{e})\, dF(x)$ (i.e., $s^{e} > 1$)

Then if IE is binding the candidate for solution is

$$s = 1 \text{ and } \alpha^{+} = \frac{c - \delta\mu \int_{q^{\circ}}^{Q} (x - q^{\circ})\, dF(x)}{\overline{q}} - \alpha^{o}$$

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

Finally, we have that $s = 1$ while IE is non-binding is not a candidate for solution. By Corollary 3 we know that it is possible to keep q° constant by decreasing s and α^{+} and this will increase B.

• *Case (ii.3)*: Assume $c \leq (\rho + \alpha^o)\overline{q} + \delta\mu \int_{q^e}^{Q} (x - q^e)\, dF(x)$ (i.e., $s^e \leq 1$) and $c < \alpha^o \overline{q} + \frac{\delta\mu \int_{q^e}^{Q} (x-q^e) dF(x)}{(\rho+\alpha^o)}$, (i.e., $\alpha^{+e} < 0$)

If IE is still binding the candidate for solution is

$$\alpha^+ = 0 \text{ and } s = \frac{c - \alpha^o \overline{q}}{\delta\mu \int_{q^o}^{Q} (x - q^o)\, dF(x)} < s^e$$

note that $s \geq 0$ because $c \geq \alpha^o \overline{q}$, and $s \leq 1$ because here $\alpha^{+e} < \alpha^+$ and therefore $s < s^e$ which in this case is smaller or equal than one.

If IE is not binding the solution is the one that

$$\max_s B$$
$$\text{s.t.} \qquad s \geq \frac{c - \alpha^o \overline{q}}{\delta\mu \int_{q^o}^{Q} (x - q^e)\, dF(x)}, s \leq 1 \text{ and } \alpha^+ = 0$$
$$\text{with} \qquad q^\circ \text{ defined by } TA.$$

Proof of Proposition 8

At $t = 1$ the researcher does research and obtains at the end of the period q_1 and A_1. She has to decide whether to do research or development during $t = 2$. If she chooses to look for a new idea she obtains at the end of the second period, q_2 and A_2 and a payoff of $\alpha_2 q_2$. At this point, she would have to decide whether to do research again at $t = 3$, obtaining $\alpha_3 q_3$ at the end of it or development obtaining $s_3(\mu q_2 - A_2)$. If instead she decides to do development at $t = 2$ she 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 she 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 she decides to do research in the second and development in the third, she obtains

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

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

$$s_3(q_2 + a_2) \geq \alpha_{3'}\overline{q}_{3'}. \tag{7}$$

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, she 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 9

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

$$s(\mu q_2 - A_2) = \alpha\overline{q}, \tag{8}$$

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

$$s(\mu q_1 - A_1) = \alpha\overline{q} + \delta\int_0^{Q}\int_{\underline{A}_2}^{\widehat{A}_2(x)} \left[s(\mu x - y) - \alpha\overline{q}\right] dH(y)dG(x). \tag{9}$$

Since by definition the function in the integral is positive in that domain, we have that the left hand side is higher in (9) than in (8) 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 10

If $A_i \equiv 0$ and $\mu = 1$ we have that the stopping rule in the first and second periods are 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

$$V = \alpha_1\overline{q}_1 + \delta s_2 q_1^o + \delta^2\alpha_3\bar{q}_3 + \delta s_2\int_{q_1^o}^{\overline{Q}}(x - q_1^o)dG_1(x). \tag{11}$$

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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