A Theory of Private Research Funding*

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Abstract

Research can be carried out in academia, or in the private sector, or as a mixture, for example as privately funded academic research. We develop a theoretical framework in which private research funding (PRF) transfers information about the value of a research project from the private sector into academia, in an incentive compatible way. PRF dominates neither pure academia nor private research. We derive predictions about the optimal sequence of research designs, and about the optimal duration of a project within different designs. For example, PRF is never optimal if not preceded by pure academical research. We compare our results with stylized facts.

Keywords: Innovation, Research Funding, Research Finance, R&D, Academia, University Finance.

JEL-Codes: L33, H52, O31.

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1 Introduction

Looking at the recent list of Nobel Prize-winners, one will find not only a wide range of research topics but also various sources of funding. In addition to the traditional forms of research, namely private (i. e., in the industry) and academic (i. e., in universities) research, a considerable number of laureates had been funded by a mixture of private *and* public funds. For example, take the Nobel Prize in physics. The 2008 winners Makoto Kobayashi and Toshihide Maskawa had never raised any private research funds and used only the basic money provided by the Kyoto University for research in particle physics. In contrast, the 2000 winner Jack Kilby had his research on semiconductor physics completely funded by Texas Instruments. One laureate of 2002, Raymond Davis Jr., detected the cosmic neutrinos, using funding from both private and public sources (for further details see Tatsioni, Vavva, and Ioannidis, 2010). Hence, also from a financial perspective, there are different roads that lead to success in research.

Nevertheless, the question arises which research design should be pursued from an economic perspective because there are significant differences between private, the mixture and academic research. Due to the target-oriented character of research of the first, rather concrete and applicable questions are investigated. Basic as well as risky research will probably become extinct. In contrast to that, the nonprofit-oriented character of the latter yields to the possibility that researchers are allowed to pursue a broader range of research (basic and applied, theoretical and experimental, etc.), respectively to trace various ideas. The granted scientific freedom implicates that a fraction of this research is not intended to provide implementable results that can be commercialized. Among these two extremes privately funded academic research as a hybrid is gaining ground. Between 1981 and 2003 private research funding (PRF) within the academic sector has increased from 16 to 22 percent (Vincent-Lancrin, 2006, p. 10). This kind of funding can potentially be seen as a boon or a bane. Arguably, if academic researchers are forced to raise private research money, their attention is drawn not to the most promising projects, but to those that the private sector likes. In addition, human resources may be wasted in the rat race for private funds. On the other hand, one could see private research funding as a beneficial mixture between public and private effort just like (ideally) in a public-private partnership (PPP).

Our main research questions result right away from these considerations: Who should carry out research? Either solely academic or private researchers or are cooperations reasonable? What is the optimal sequence if there are differences in the divers research stages of a project? And who should decide about the way research is optimally done? The researchers themselves are hardly capable to do so. Thus, one could think of a welfare maximizing research designer. Who it might be, he is in need of additional information.

In order to answer these questions, we scoured for existing publications discovering that even though the literature on research in general as well as particularly on PPP (see e.g. Maskin and Tirole (2007), Hart (2003), and Murray, Aghion, Dewatripont, Kolev, and

Stern (2009)) is immense, hardly any work considers private research funding. We close this gap by extending the model of Aghion, Dewatripont, and Stein (2008). In their discrete model, Aghion, Dewatripont, and Stein assume that innovation occurs in a number of steps. Each step can be carried out in the private sector, where researchers are more determined, or in academia, where researchers demand lower wages because they appreciate academic freedom. With increasing steps of innovation, the product progresses towards marketability, so research becomes more urgent. A welfare maximizing policy maker (the dean, or rector, or director, in the following called the *research designer*) should then transfer the research line from academia to the private sector in order not to risk the project success.

For computational ease, without changing any comparative statics, we take a continuous-time version of this model and in order to endogenize research funding and, we introduce a delegation problem: The research designer has neither information on the valuation of research projects nor the control over the researchers‘ strategy choice. To get an idea if the researchers work auspiciously, he could ask the private sector. Therefore, we add one modeling component, assuming that the private sector can gather information on the marketability of the final product – at a cost. This information is valuable for the research designer, hence he wants to implement an incentive-compatible contract with the private sector to get the information truthfully. One way to do so is by asking the private firm to contribute to research funding (PRF), pledging part of the proceeds at the final date when the product becomes marketable. In equilibrium, the firm gathers the information on the product value, and invests if and only if the information is positive. Hence, the research designer pursues only those research lines that receive PRF – not only for monetary reasons but also because the PRF serve as a signal for promising research projects. In a nutshell, the research designer has to decide with the help of the private sector which kind of research is welfare maximizing. In the end, there are three endogenous research designs: pure academia, privately funded academia, and private research.

Our model produces a number of qualitative and quantitative results. Qualitatively, projects typically start in pure academia, then obtain PRF, and finally are handed over to the private sector, where products reach marketability. Potentially, some of these steps are leapfrogged, but the order never changes. However, a project is never started with PRF right away. It is either initiated in the private sector, or in pure academia (see Figure 1).

Quantitatively, we can calculate the optimal date for inviting private money into academia (t_c), and the optimal date for completely switching to the private sector (t_s). Surprisingly, t_c depends on the cost of the information, the likelihood of positive information, and wages in academia, but *not* on the potential value of the final product. In a sense, there is a period in which academia should be immune to market forces. The date t_s depends, among other things, on the potential value (the more valuable a final product, the earlier a research line should be handed over to the private sector) and on the wage differential between academia and the private sector (the higher the wage differential, the longer a research line should remain in academia). We can also calculate the fraction of the academic

Figure 1: Possible Endogenous Sequences of Research Designs

Idea → Pure academia → Academia with PRF → Private sector → Marketable product
Idea → Pure academia → Academia with PRF ——————→ Marketable product
Idea → Pure academia ——————→ Private sector → Marketable product
Idea → Pure academia ——————————————→ Marketable product
Idea ——————————————→ Private sector → Marketable product

Idea → No research → No marketable product

budget that is covered by private funding, finding that the budget is never covered completely. However, an increasing potential value of the final product comes along with an increasing fraction of research funding of the academic budget. Furthermore, the amount of PRF does not depend on the potential value of the product, but the switching date t_s is brought forward with an increasing value. Hence, the private sector does not finance research lines of limited value at all. Either the research designer has the possibility to close the research lines or they are finished inside pure academia. In this case it is impossible for the researcher to raise PRF without being subsidized by a public institution because the compensation for a cooperating firm would not be sufficient to incentivize it. It indirectly finances research lines of medium marketability. Research lines of extreme value are started in the private sector right away.

The remainder of the paper is organized as follows. After giving an overview over related literature, we survey the most important stylized facts concerning research funding. In section 2, we introduce and solve the basic version of the model, with only an academic and a private sector. It is deduced from the model of Aghion, Dewatripont, and Stein (2008) but in a continuous version. We then add the possibility to get information about the expected value of a research project, at a cost. Section 3 introduces research funding as an institutional design to transfer information from the private sector into academia. Section 4 concludes. Proofs are in the appendix.

1.1 Related Literature

Our paper combines two strands of literature, innovation and finance. There is a mass of finance literature focusing on the allocation of capital in the presence of asymmetric information. In lights of this, Stiglitz and Weiss (1981), and Meza and Webb (1987) investigate the required subsidies of entrepreneurs and Boadway and Keen (2006) conclude that the results depend on the expectations about the project return distributions. In a sense, we jump on this train in order to implement this topic into R&D, but we introduce PRF as a signal for auspicious research. In line with this, the work of Leland and Pyle (1977) observe investments in a project by an entrepreneur as a reliable signal for the quality of a firm. Holmström and Tirole (1997) also explore entrepreneurial finance, but they concentrate on the interaction of informed financiers with less informed investors in a moral hazard framework. Instead of moral hazard, we rather focus on adverse selection and a research designer who wants to balance the existing asymmetry of information. He fulfills the task of the financial intermediary balancing the incentive problems between borrowers and lenders considered in the monitoring framework of Diamond (1984). In addition, Alam and Walton (1995) and Hubbard (1998) point out that the problem of asymmetric information yields not only to financing constraints between entrepreneurs and financiers like Akerlof (1970) elaborate, but particularly to financial restrictions in R&D.

We also contribute to innovation literature. Like Aghion, Dewatripont, and Stein (2008), we assume a fundamental tradeoff between academia and the private sector, respectively a tradeoff between academic freedom, defined as the granting of control rights to the researchers, versus focus. In doing so, we exclude any incentive scheme, job-design or priority rule and abstract away from a broader and more institutional view of the role of academia like Dasgupta and David (1994). Thus, the main difference to industrial research is that the researchers employed in the academic sector are free to establish new research lines and to experimentalize. In accordance with Aghion and Tirole (1997), Grossman and Hart (1986), Hart and Moore (1990), Hart (1995), we reconsider that scientists appreciate that freedom and value creative control. Thus, we follow the accepted thesis that the wage in the academic sector is less than in the private sector, where the researchers have to be compensated for the loss of creative freedom.

In contrast to them, we focus rather on monetary arguments and patterns of finance than on academic freedom in terms of intellectual property rights (IPR). Furthermore, we implement an intermediate sector (privately funded) and define accordingly two switching dates: the one from academic to funded research and the one from funded to private research. Additionally, we implicate information cost in order to eliminate the asymmetric information with respect to the marketability of research projects. Last but not least, we use the proofs and intuitions of Aghion, Dewatripont, and Stein (2008) to expand our model to the case with private research funding.

We only consider implicitly the idea of academic freedom in the sense of delegation of authority to scientists. Aghion, Dewatripont, Hoxby, Mas-Colell, and Sapir (2009) yet take a step forward and stressed the meaning of openness, the free flow of ideas across academic institutions, as a central attribute of academia. The recent paper of Hellmann and Perotti (2006) is a proposal for that intention. It also models research as a multi-stage process and endogenizes the choice between academic and private research. Furthermore, it contrasts the free flow of ideas in academia with the more controlled informational exchange that occurs in private firms.

Besides, we abstract away from any incentive schemes which are already implemented in private research institutions in reality. Geuna and Martin (2003) examine the advantages and disadvantages of performance-based funding in comparison with other approaches to funding. Moreover, Aghion, Dewatripont, Hoxby, Mas-Colell, and Sapir (2009) discover in a yet another approach that university governance in terms of autonomy and competition affects inventive research output in a positive way. Alternatively, Banal-Estañol and Macho-Stadler (2010) propose a framework to analyze the effects of scientific and commercial incentives in R&D organizations. They show that commercialization incentives influence the choice of research projects and deduce an optimal incentive scheme respective to the researcher's characteristics. Last, but not least Choi (1993) develops a model of sequential innovations with a variety of research lines and compares two alternative systems of enforcing patent law to provide proper incentives for R&D.

Another related paper deals with that subject in a different way. Indeed, Takalo and Tanayama (2010) study a similar idea of research funding in the presence of asymmetric information which can be eliminated by subsidies serving as signals. Opposed they observe the distinction of private and public funding with financing restrictions. They argue that under certain conditions, public R&D subsidies reduce the asymmetric information by dint of reducing financing constraints of firms.

At last and continuative to the work of Aghion, Dewatripont, and Stein (2008), there is some literature treating the consequences of the different kinds of research. Murray, Aghion, Dewatripont, Kolev, and Stern (2009) corroborate the risk of decreasing innovation by detecting that restrictions of academic freedom reduce the variety in basic research. Particularly, openness and academic freedom may increase the overall flow of research output in basic as well as in applied research. Another approach of Aghion, Dewatripont, Hoxby, Mas-Colell, and Sapir (2009) investigates the correlation of autonomy and research output of universities and assesses a positive relation. The authors add by way of explanation that even greater funding is likely ineffective as measured by research output, if there exist no careful and balanced commitment to openness as well as to freedom (see Murray, 2007).

1.2 Stylized Facts

In the past three decades, both R&D expenditures and research funding have increased nearly all over the world, especially in the OECD area (Vincent-Lancrin, 2006, p. 2). Private research and higher education research (in the sense of academic research) alike have gained in importance.

Actually, higher education R&D has grown more rapidly in absolute and relative terms than in any other sector, the expenditures have tripled and the number of researchers has more than doubled between 1981 and 2008 (Vincent-Lancrin, 2010, p. 4). Despite the public prominence in the financing structure, more and more funding is provided by private sources. Indeed, the government performs 80% of basic research and still allocates the bulk of the funds for academic research (72% in 2008), but its aggregate share is decreasing (-6% between 1981 and 2006). Meanwhile, the share of the private sector in academic research funding has doubled since 1981 but is still at a relatively low level. Vincent-Lancrin predicts that, should these trends continue, we will see academic research half privately and half publicly funded within the OECD given the different capitalization of the business and academic sectors.[1]

With this general information in mind, we present some stylized facts. Some of these facts motivate our modeling choices. Others can be related to our empirical hypotheses. Having said that, please note that the available data is relatively scarce, hence the following "facts" should be treated with some caution.

Fact 1 *C. p., the wage in the private sector exceeds the wage in the academic sector.*

In general, academic researchers earn less than researchers in the private sector. This gap is especially large for fundamental research, i. e., for research projects where the marketable final product is still far ahead, or where the probability that the project will never succeed is still significant. For instance, academic political scientists earn just about half of the wage of private employed researchers. In 2010, a political researcher earned an average of $59.940 in academia, but $104.390 in the private sector. Employed mathematicians earned $72.840 in academia versus $114.820 in the private sector in 2010.

In contrast, research areas carrying out application-oriented research (high probability of a marketable product in the end) in both sectors, possess a small wage discrepancy. Consistently, a life scientist working in an U. S. university earned in 2010 on average $66.810, whereas wages in the amount of $78.150 are paid averaged in U. S. private sector research. Biological scientists are serving as another example. In 2010 they got $59.200 in the academic and $77.050 in the private research sector on average.[2]

Walker, Vignoles, and Collins (2010) study this fact in a more general framework by comparing the salaries of higher education academics in the UK with those of other comparable professionals. Their findings coincide with the estimation of UK and U. S. academic wages by Stevens (2004), namely that academic employees earn less than graduates working in the non-academic sector.

Fact 2 *C. p., private research is more likely to be marketable.*

The lion's share of research is carried out and financed by the private sector. Between 1981 and 2008, the share of R&D performed by the business sector has yet increased from 65.4% to 70% of the total R&D effort in the OECD area (Vincent-Lancrin, 2010,

[1] For details see "Higher Education to 2030," by the Centre for Educational Research and Innovation.
[2] Data are available from the Bureau of Labor Statistics on www.bls.gov/data/.

p. 2). Because of the profit-orientated character of private research, almost only research of commercial value is executed. This feature is evidenced by the amount of patents announced in the member states of the Patent Cooperation Treaty (PCT). In 2008, the business sector accounted for approximately 84% of total PCT filings. However, the share of the business sector is diverse, ranging from 94.2% in Sweden to 40.9% in South Africa. Front-runner among these firms was the Chinese company Huawei Technology, employing approximately 42 000 R&D personnel, with the highest number of PCT filings (1 737), while Panasonic Corporation and Philips were ranked second and third.

Hence, basic research projects as less restricted to commercial success exist entirely in academia. Besides, the Bayh-Dole Act of 1980 enabled academic researchers to pursue ownership of an invention. As a consequence, academic research has undergone a change, more and more ideas have been patented. The university sector in the PCT member states accounted for a significant share of total PCT filings of about 6%. U. S. universities dominated the list of top PCT applicants. The University of California, occupying 10 700 research employees, filed 345 PCT applications, hence twice as much as the following MIT. In this respect, the most effective university patented 25% less per R&D employee than Huawei Technology. In comparison with the total amount of patent filings announced by the business sector, the quantity of academic patents seems to be just a drop in a bucket. This may be up to the associated probability of failure. Thus, leaving the choice of research method in the hands of the researcher represents a risk, that a scientists chooses not the most promising way of research.[3]

Fact 3 *C. p., an increasing expected value of a research project comes along with a rising probability of success, respectively probability of marketability.*[4]

First and foremost this becomes approved if one thinks of the monetary value of research projects. For instance, life science-based innovations (drugs) could be implemented and converted into money more easily than psychological innovations (new therapies). In reality, determining the effective value of an innovation is quite complex. A credible indication of the valuation could be provided by means of articles, citations or reference book-selling.

If scientific articles are pulled up as a measure for the valuation of an innovation, it is accordingly possible to distinguish between and classify different fields of research. In total, the number of scientific articles being published increased by a high degree of 40% between 1988 and 2008 to an amount of about 700 000 within the OECD area.[5] 31% thereof are ascribable to clinical medical, 15% to biomedical, 12% to physical, and 10% to chemical articles. Together with other "hard" sciences and engineering they represent the

[3]See the "World Intellectual Property Indicators 2009" by the World Intellectual Property Organization.
[4]This might sound very trivial. Nevertheless, this correlation is important for our further analysis.
[5]Similarly, the number of newly published academic books has increased.

bulk of academic research articles. The remaining fields of research, such as psychology, social and health sciences, and professional fields accounting for about 10% of the OECD article output. Hence, we make an educated guess that applied research lines tend to yield to more countable results, although not every project carried out is successful. Due to the fact that “soft” science projects are often theoretical, the results are less commercialisable or marketable, while we also have to distinguish between every single project.

Fact 4 *C. p., an increasing probability of marketability comes along with an increasing fraction of research funding of the academic budget.*

Taking into account the statistics from the U. S. academic research sector, one can notice that research funds for life sciences and engineering exceed the funds for social science, psychology, mathematical and physical sciences. Particularly, the special field of life sciences, including agricultural, biological, medical and life sciences itself, relied on non-federally funds of \$8.4 billion in public universities, which accounts for 45% of the total R&D expenditures. Alongside, the departments of engineering, mainly civil, electrical and mechanical engineering had an amount at their disposal of \$2.6 billion, in other words 49% of the R&D expenditures are non-federally funded. In contrast, the environmental as well as the physical sciences in public U. S. universities had to get along with just a fraction of \$219 million and \$135 million, which is up to a share of only 34% of the total expenditures.[6] A reasonable statement for that phenomenon will be executed by our model.

Some of these stylized facts enter into our set of assumptions, others correspond to results of our model. We will refer to these facts within the model, and later in the conclusion.

2 Framework

Like Aghion, Dewatripont, and Stein (2008), we consider a step-by-step development of a valuable product (a drug, for instance) in which discoveries generated in one stage serve as essential inputs into the next. Starting point is a basic idea I_0 which then goes through a number of stages to become refined in each case, the past stage was successful. In contrast to Aghion, Dewatripont, and Stein, we consider a continuous number of T stages. Hence at each date $t \in [0;\ T)$, starting from stage I_t, if research is carried out successfully for dt periods, the next stage I_{t+dt} is reached. At the final stage I_T, the market stage is reached; the project can be sold. With probability q, it is worth V, otherwise it is worthless (for example because the drug is never admitted).

[6] See the “Academic Research and Development Expenditures: Fiscal Year 2007” by the National Science Foundation (www.nsf.gov/statistics/nsf09303/pdf/nsf09303.pdf).

Each of the required steps to complete a research project can be carried out in two different ways, in *academia* or in the *private sector*. As the main difference, researchers enjoy academic freedom in academia, but are forced to predefined research strategies in the private sector. To fix ideas, assume that in each logical second, there is a variety of research strategies (theoretical vs. empirical, exploratory vs. constructive, ...). Researchers personally prefer strategies at random, but a fraction $\lambda > 0$ of strategies is bound to fail. In academia, because of academic freedom, researchers can choose the strategy they want. As a consequence, projects fail with probability λ. This assumption is in line with stylized fact 2. In the private sector, researchers are forced to choose a promising strategy, thus projects never fail. Following Aghion, Dewatripont, and Stein (2008), we assume that researchers value creative control, i. e., their academic freedom. Therefore, researchers in the private sector must be compensated for the fact that, with probability λ, they cannot choose their preferred strategy. If the competitive wage in academia is w_a, the wage in the private sector must be $w_p = w_a + \lambda\, z$, where $z > 0$ is a researcher's utility from following his preferred research strategy. This assumption is based on stylized fact 1. Setting the outside option to an exogenous w_0, then $w_a = w_0$ and $w_p = w_0 + \lambda\, z$.

Examining the model in continuous time, a researcher earns $dt\, w_a$ for working in academia for dt periods, and $dt\, w_p$ for working in the private sector. In academia, the project fails with probability $dt\, \lambda$. Accordingly, after time t has elapsed, a project in the academic sector has failed with probability $F(t) = 1 - e^{-\lambda t}$. The according density function is $f(t) = \lambda\, e^{-\lambda t}$, and the instantaneous failure rate is exactly $f(t)/(1 - F(t)) = \lambda$. A project in the private sector never fails.

2.1 The Basic Tradeoff between Academia and Private Research

Consider now a social planner (the research designer) who wants to maximize the expected payoff of a research project. In order to do this, he needs to plan at which time to conduct research in academia, at which time to switch to the private sector, and possibly switch back to academia. Each research stage can possibly be carried out in academia or in the private sector. However, we can show that optimally, one switches at most once, and always from academia to the private sector. The proof of the following remark is in the Appendix.

Remark 1 *If research is optimally carried out privately at some date, it remains there until it is finished.*

As a consequence, there is a single possible switching date t_s at which the project is handed over to private research. This result is the continuous-time equivalent of Aghion, Dewatripont, and Stein (2008, Lemma 1). Now given a switching date t_s, the probability that the product reaches marketability is $1 - F(t_s) = e^{-\lambda\, t_s}$. Before date t_s, it fails with instantaneous probability λ, which is the probability that the wrong strategy is chosen by the researcher. Once it reaches t_s, the project is handed over to the private sector and can no longer fail. Hence, the expected value itself is $(1 - F(t_s))\, q\, V$, because the product is marketable in the end only with probability q, in which case it yields a value of V. The expected wages for research in the private sector are $(1 - F(t_s))\, w_p\, (T - t_s)$. Aggregate wages in academia, conditioned on the non-failure of the project, are $(1 - F(t_s))\, w_a\, t_s$. Therefore, the expected payoff consists of $q\, V - w_p\, (T - t_s) - w_a\, t_s$, weighted with the probability that the project reaches t_s, thus $1 - F(t_s)$. However, even if the project fails in between the initial stage and the switching date, some wages must be paid to academia. The aggregate depends on the moment of failure. The aggregate expected wage, if the project fails, is then $\int_0^{t_s} w_a\, t\, f(t)\, dt$. Now aggregating all terms, the expected payoff from the project is

$$\Pi = (1 - F(t_s)) \Big[q\, V - w_p\, (T - t_s) - w_a\, t_s \Big] - \int_0^{t_s} w_a\, t\, f(t)\, dt. \tag{1}$$

Using the first order condition, the payoff-maximizing switching date is

$$\frac{\partial \Pi}{\partial t_s} = -\, e^{-\lambda\, t_s} \big(\lambda\, q\, V + w_a - w_p\, (1 + \lambda\, (T - t_s)) \big) = 0, \tag{2}$$

$$t_s^* = T - \frac{q\, V}{w_p} + \frac{w_p - w_a}{\lambda\, w_p}. \tag{3}$$

Some properties follow immediately. *First*, the duration of the time in private research $T - t_s^*$ does not depend on the total development length T. The intuition for this result goes as follows. When a project is very far from completion, the cost of losing the project is comparably low. Consequently, it is cheaper to pay the low academic wages. Later, when a project is closer to completion, it should no longer be put at risk. Hence, one should then switch to the private sector. So to speak, the project must beef up before it is taken over by the private sector. Now if, c. p., the aggregate duration of development is longer, the time until the project has beefed up enough is accordingly longer. The time spend in the private sector is not affected, though. *Second*, the higher the expected value of the final product $q\, V$, the earlier one should switch to the private sector. This comparative static will be important in the following sections. Of course, if the project is more valuable, it should not be put at risk. *Third*, t_s^* depends directly on the wage differential $(w_p - w_a)/w_p$, in relation to the default probability λ in academia. The higher the wage markup in the private sector, the later one should switch because private sector research becomes relatively more expensive. *Fourth*, t_s^* depends negatively on the academic wage w_a itself. The higher w_a, the earlier the project should be transferred to private sector research.

Possibly, it is optimal to start the project in the private sector right away. Formally, $t_s^* = 0$, which happens if

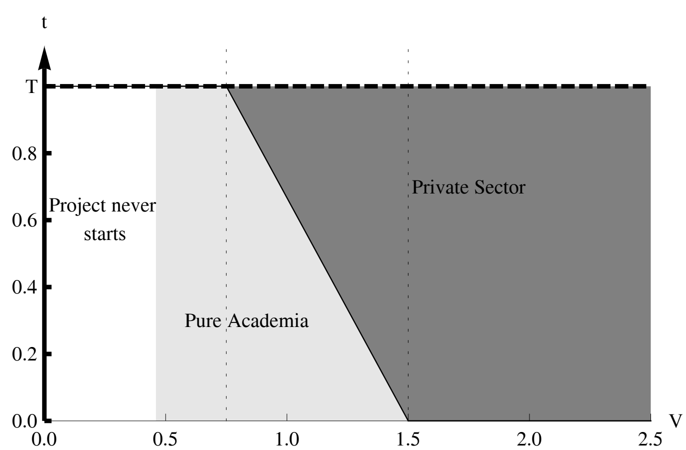
$$t_s^* = 0 \qquad \Longleftrightarrow \qquad q\, V \geq T\, w_p + \frac{w_p - w_a}{\lambda}.$$

Because there is no switching *to* academia, this implies that the complete research is privately funded. This happens if V or q are large, or if T is small, hence if the project is rather applied. To the other extreme, it may be optimal to start and finish a project in academia. Formally, $t_s^* = T$, which happens if

$$t_s^* = T \quad \Longleftrightarrow \quad q\,V \leq \frac{w_p - w_a}{\lambda}.$$

This case occurs if q or V are low, hence if the project is rather abstract. We need to consider one more constraint. If V is very low, the optimal strategy will be to not pursue any research at all. The constraint obtains from plugging the optimal t_s^* into the expected profit (1) and checking whether the result is positive. The calculations are in the Appendix.

Figure 2: No Research Funding



In order to summarize the first results, we illustrate them in Figure 2. Exemplary you can see the dependence on the switching date on the potential value or rather, it shows the optimal choice between academia and the private sector for parameters $\lambda = 0.5$, $T = 1$, $q = 0.67$, $w_0 = 0.25$, and $z = 0.5$ (remember that $w_a = w_0$ and $w_p = w_0 + \lambda\, z$). The final value V is kept variable (here between 0 and 2.5). For $V \leq 0.46$, the expected payoff is negative. Therefore, a research project never starts at all. For $0.46 \leq V \leq 0.75$ (first dotted line), all research is carried out in academia. For $V \geq 1.5$ (second dotted line), all research is done privately. But for $0.75 < V < 1.5$, a research project is started in academia and finished in the private sector. The higher the value V, the earlier the project is transferred to the private sector. For each V, a possible research path can be seen, starting on the V-axis and then moving upwards with progressing time. For example, for $V = 1$, research remains in academia until date $t = 0.67$, then it is switched to the private sector for the last 0.33 periods.

2.2 Qualified Information on the Marketability of the Final Product

Until now, we orientated ourselves by Aghion, Dewatripont, and Stein (2008) and derived similar results. Now we extent our benchmark model to the case with a qualified information. The final product has a value V with probability q. Henceforth assume that, by spending a cost c, the research designer can find out whether the product will be valuable or not. If he, with probability q, finds that the product will be valuable, he will advance the switching date t_s in comparison to the above section. If he, with probability $1-q$, finds that the product will not be valuable, he will cancel the project altogether, and not pay any more wages. This might sound very unrealistic, because typically the research designer can neither deny paying wages to academic researchers nor dictate the research topic. Nonetheless he can influence the researcher to give up the project, and we assume him to be successful.

Let t_c denote the date at which the research designer collects the information at cost c. Now, having waited until t_c, the project may already have failed, in which case the expected wage aggregates to $\int_0^{t_c} w_a\, t\, f(t)\, dt$. With probability $1 - F(t_c)$ the research project is still alive at date t_c and he spends c. Either he gets a negative information (with probability $1-q$) and thus closes the research line. Or he receives a positive information (with probability q), carries on and leaves the project in academia until date t_s (which may now differ from the above switching date). However, a project might fail in between the dates t_c andl t_s despite a positive information. However, the wage $q \int_{t_c}^{t_s} w_a\, t\, f(t)\, dt$ has also to be paid until the date of failure. The research line is still alive at date t_s with probability $q\,(1 - F(t_s))$. From this time on, everything is as before. Consequently, the aggregate expected payoff is

$$\begin{aligned} \Pi = {} & q\,(1 - F(t_s)) \Big[V - w_p\,(T - t_s) - w_a\, t_s\Big] - (1 - F(t_c))\, c \\ & - \int_0^{t_c} w_a\, t\, f(t)\, dt - q \int_{t_c}^{t_s} w_a\, t\, f(t)\, dt. \end{aligned} \tag{4}$$

The optimal dates t_c^* and t_s^* are chosen according to the first order conditions

$$\frac{\partial \Pi}{\partial t_c} = \lambda\, e^{-\lambda\, t_c} \big(c - (1-q)\, t_c\, w_a\big) = 0,$$

$$t_c^* = \frac{c}{(1-q)\, w_a}, \tag{5}$$

$$\frac{\partial \Pi}{\partial t_s} = -\, q\, e^{-\lambda\, t_s} \big(\lambda\, V + w_a - w_p\,(1 + \lambda\,(T - t_s))\big) \tag{6}$$

$$t_s^* = T - \frac{V}{w_p} + \frac{w_p - w_a}{\lambda\, w_p}. \tag{7}$$

There are some interesting phenomena. First, it is never optimal to gather the information as soon as possible, $t_c > 0$. One might think that the information about the value should be received as soon as possible, thus right at the initial of the development of a product. But surprisingly, this procedure never leads to an optimal financing structure. Because of the existing probability of failure in academia it is advisable to await the development of a project some time. Otherwise, a cost would be spend too early.

Second, the information date t_c depends on the probability of negative information, but not on V. Because $t_c > 0$, projects are never started with the information right away, there must be a preceding exploratory phase. If a project is only of marginal expected value, the information should be collected very early. With increasing success probability q, the information date t_c is postponed, but the timing of the switch to the private sector is unaffected.

Third, in comparison to the case without any information cost c, the switching date t_s is brought forward by $(1-q)\,V/w_p$, independent on c. Like in the case without a qualified information, the duration of the time in private research $T - t_s$ does not depend on the total development length T, whereas the duration until the information is gathered ($T - t_c$) depends on T.

Fourth, it is obvious that the wages also influence the dates t_c and t_s. Precisely, an increasing academic wage w_a leads to an earlier information date t_c as well as switching date t_s. This is quite logical. The more expensive a research project becomes, the earlier the research designer wants it to be transferred to the private sector. With a rising difference between academic and private wage (λz), an opposite trend related to the switching date t_s is observable. Private research becomes more costly compared to academic research. Consequently the project has to be transferred at a later date from the point of view of a social planner.

Finally, comparing the above t_s and t_c, we find that $t_s \geq t_c$ only if

$$V \leq w_p\,T - \frac{w_p\,c}{(1-q)\,w_a} + \frac{w_p - w_a}{\lambda}. \tag{8}$$

If this condition fails to hold, then it is optimal to switch to the private sector right after getting the information. It can never be optimal to switch to the private sector first and then to collect the information later. Consequently, setting $t_s = t_c$, the expected payoff then becomes

$$\Pi = q\,(1 - F(t_c))\left[V - w_p\,(T - t_c) - w_a\,t_c\right] - (1 - F(t_c))\,c - \int_0^{t_c} w_a\,t\,f(t)\,dt.$$

The first order condition yields

$$\frac{\partial \Pi}{\partial t_c} = e^{\lambda\,t_c}\Big(q\,(w_p - w_a) - \lambda\,\big(t_c\,w_a - c + q\,(V - t_c\,w_a - (T - t_c)\,w_p)\big)\Big)$$

$$t_s = t_c = \frac{c - q\,\big(V + w_a/\lambda - w_p\,(T + 1/\lambda)\big)}{q\,w_p + (1-q)\,w_a}. \tag{9}$$

Here, some comparative statics are immediately apparent. As mentioned in the previous section, a higher potential value V leads to earlier switching to the private sector. Not very surprising, higher information cost c as well as a larger aggregate research time T and a greater wage differential entail later switching.

There is one more constraint. For very low V (or low q, or high wage levels), one should never start the research project in the first place. The expected wage bill would exceed the expected reward from finishing the project. Both expected aggregate costs and expected final value depend on the research design. The condition looks different depending on whether the project is carried out only in academia, only in the private sector, or switches in between. Therefore, conditions are given at the beginning of the Appendix.

Figure 3: First Best with Information

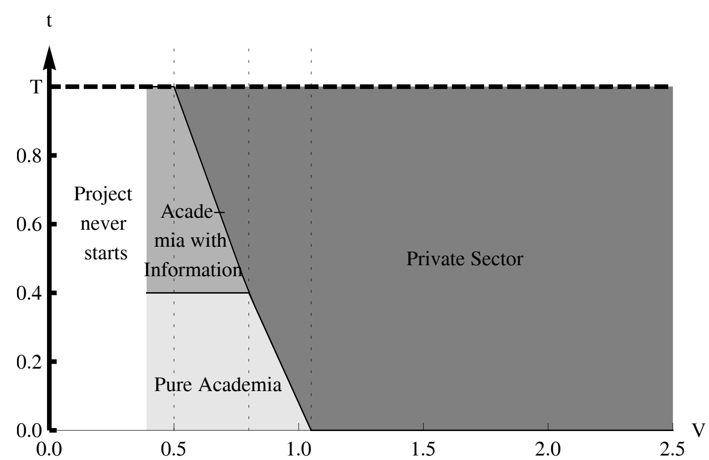


Figure 3 shows again some time paths of research for different V ($c = 0.033$, all other parameters are as before). Taking the same exemplary potential values into account, there are several possible scenarios. For $V \leq 0.39$, the expected payoff is negative and no project is actually started. For $0.39 \leq V \leq 0.5$ (first dotted line), the research project remains in academia until the end if the information on the marketability of the project gathered at date $t_c = 0.4$ is positive. If it is negative, the project is stopped right away. For $0.5 < V \leq 0.8$ (second dotted line), the information is also collected at date $t_c = 0.4$. After this date, an academic researcher may work on the project for some more time. However, at some date t_s, the project is transferred to the private sector. The larger the value V, the earlier the project is transferred. For $0.8 < V \leq 1.05$ (third dotted line), the project is started in academia, until some date t_s, the project is directly transferred to the private sector. There is no need of further information. For $V > 1.05$, the project is started right away in the private sector. As you can see in comparison to the case without a qualified information, the switching date t_s is brought forward. The $V = 1$ project of the previous section is now handed over to the private sector almost right after its initiation.

3 Research Funding

In reality, the question of whether a product will have a market value or not can often not be answered inside academia. Rather, it is firms who know best how much money a product may earn. Therefore, we now make the assumption that a third party (firm) can gather the information on whether the product will be valuable or not. As a consequence, the research designer (principal) will have to design a mechanism to get the information from the firm. He needs to design a contract such that the firm has sufficient incentives to participate, to gather the information at cost c, and to report the information truthfully.

One such contract looks as follows. At date t_c, the firm must invest an endogenous amount I into the project (research funding). In return, the research designer promises the firm an endogenous fraction γ of the final return V. For example, if the final product leads to a patent, the research designer could grant the firm the permission to use the patent for free. One could also think of other concessions like cash-flow rights or property rights.

In principle, the way the contract is written might influence the optimal dates t_c and t_s. However, we will show that a research funding contract one can achieve does not cause delegation cost, thus t_c and t_s are unaffected. Let us now derive such a research funding contract. First, the firm must be willing to gather the information. If time t_c is reached and the firm spends c, it will invest I with probability q (only if the information is positive). The project will then be successful with probability $1 - F(t_s)$, in which case the firm will collect $\gamma\, V$. If the firm does not gather the information and always spends I, it gets $\gamma\, V$ with probability $1 - F(t_s)$. Hence, incentive compatibility requires

$$(1 - F(t_s))\,\gamma\, q\, V - (1 - F(t_c))\,(c + q\, I) \geq (1 - F(t_s))\,\gamma\, q\, V - (1 - F(t_c))\, I. \quad (10)$$

Second, the firm must be willing to participate in the first place. In other words, the firms must be discouraged from always withholding research funds and thus sending the negative signal. The participation constraint requires

$$(1 - F(t_s))\,\gamma\, q\, V - (1 - F(t_c))\,(c + q\, I) \geq 0. \quad (11)$$

In equilibrium, assuming that the research designer holds all market power, he will choose γ and I such that both inequalities will bind. Solving (10) and (11) yield the optimal amounts

$$I = \frac{c}{1-q} \qquad \text{and} \qquad \gamma = e^{\lambda\,(t_s - t_c)}\,\frac{c}{q\,(1-q)\,V}. \quad (12)$$

These equations apply only if there is research funding, hence if condition (8) of the previous section holds. Otherwise, the project is turned private right away at some date t_c. At this date, the firm who acquires the project spends c and gets the information, but it does not need to be incentivized to do so; it then owns the project.

At this point some comparative statics are evident as well. If V goes up, the required γ decreases. Accordingly, the fraction of V does not need to be as high as before to compensate the firm for the investment of I. Increasing cost c result in a higher I as well as in a higher γ. This is based on the fact that the information cost reduce the expected payoff of the firm. To be profitable, the firm is forced to invest a higher I in the project and hence demands a higher fraction of the potential value γ. Additionally, according to Figure 1, the possible sequences of research designs can be summarized.

Remark 2 *Depending on the market value V, there are six possible sequences of research designs. If at all, a project is either purely academic, academic with PRF, or purely private. Typically, it starts in academia, obtains PRF, and is finally handed over to the private sector. Possibly, the PRF is skipped.*

Remark 2 is potentially more illuminative in the regimes it excludes, not in the regimes it itemizes. First, pure academia can only precede research funded academia, and research funded academia can only precede the private sector. A project is never started in the private sector and then turned to academia (this is already a consequence of Remark 1). Second, research funding is *always* preceded by pure academic research, no matter what the parameter constellation is (this is a consequence of (5)). Research projects should never be required to apply for research funding right away; if not started in the private sector, they should always cope without research funding for some time (and sometimes, for high V, even until they are switched directly to the private sector). We discuss the normative implications of these findings in the conclusion in section 4.

Figure 4: Research Funding

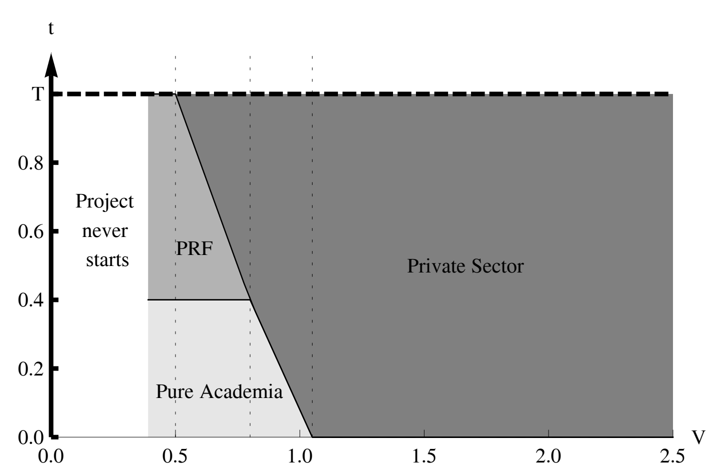
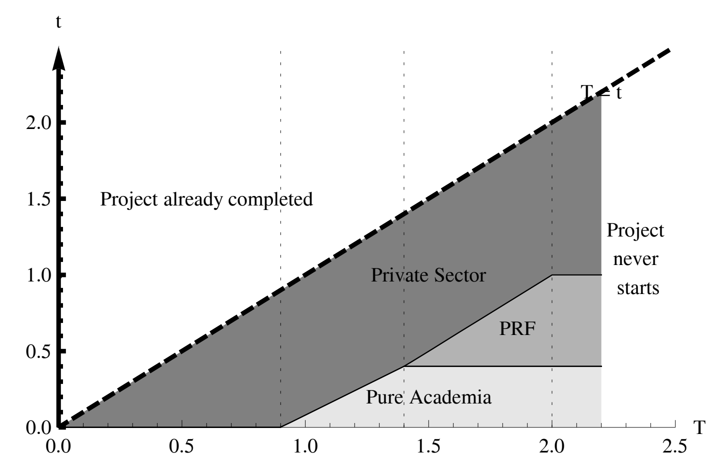


Figure 4 shows again exemplary the time paths of research for different V. For $V \leq 0.39$ no research is carried out. For $0.39 \leq V \leq 0.5$ (first dotted line), the research project remains in academia until the end. However, it is a purely academic project only until $t_c = 0.4$. At this date, the researcher needs to take in research funding. If he is unable to do so, the project is stopped. For $0.5 < V \leq 0.8$ (second dotted line), the researcher still needs to get in funding at date t_c. After this date, he may work on the project for some more time. However, at some date t_s, the project is transferred to the private sector. The larger the value V, the less dependent on private research funds is the researcher because the project is transferred to the private sector earlier. For $0.8 < V \leq 1.05$ (third dotted line), the project is started in academia, until some date t_s, the project is directly transferred to the private sector. There is no scope for research funding. For $V > 1.05$, the project is started right away in the private sector. Since the delegation does not involve agency costs, figures 4 and 5 are almost identical. When it is optimal to collect the information in figure 4, it is also optimal to have research funding in figure 5.

Figure 5: Research Funding – Alternative Illustration



Alternatively, the scenarios can be illustrated like in Figure 5. In contrast to the previous diagram, the possible research designs are shown according to the required development time. The total development length is kept variable (here between 0 and 2.5), all other parameters are as before. For $T \leq 0.9$ (first dotted line), all research is carried out privately because the duration until the project can be completed is very short. For $T \leq 1.4$ (second dotted line) the project is handed over directly from academia to the private sector without any research funding. Only a project with $T \geq 1.4$ passes through all possible research designs. It starts in pure academia, is privately funded after some time has elapsed, and is finally transferred to the private sector. The longer the time span to finalize the project, the longer is the period of private research funding until $T \leq 2$ (third dotted line). However, if the time to develop a project is very long, in concrete terms $T \geq 2.2$, it is never started. The calculation is in the beginning of the Appendix.

One can now use this model to derive further results. One question seems to be of major importance. What is the relation of the amount of research funding, I, to the aggregate bill in academia. Here, we have only one cost factor, so we can compare research funding to aggregate wages in academia. Consider expected payments within one project. The total budget (expected wage expenditures) in academia is

$$B = q\,(1 - F(t_s))\,t_s\,w_a + \int_0^{t_c} w_a\,t\,f(t)\,dt + q\int_{t_c}^{t_s} w_a\,t\,f(t)\,dt. \tag{13}$$

Besides, expected revenues from research funding are $q\,(1 - F(t_c))\,I$.

Figure 6: Research Funding as a Fraction of Total Academic Expenditure

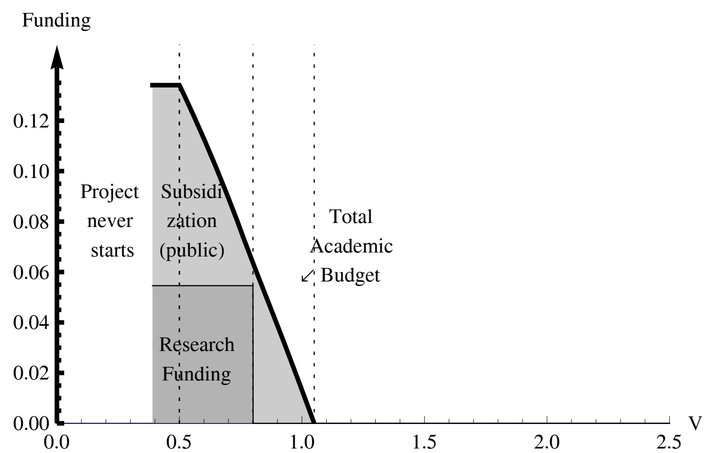


Figure 6 shows the amount of research funding (light gray), the total budget of academia (solid curve), and the funding gap that must be filled by public subsidies (dark gray) for varying V (all other parameters as in the above figures). First, note that there are some parallels between Figure 4 and Figure 6. For example, research funding is positive in Figure 6 only if it occurs in Figure 4. And when all research is done by private firms, the academic wage bill is zero, of course. Of course, the same happens if no research is carried out (that is the case if $V < 0.39$, as illustrated in Figure 4 as well). Two things are especially interesting in Figure 6. First, given that research is pursued, the academic wage expenditure is decreasing, so research funding as a funding source for academia is an increasing function in V. Second, research funding does not exceed aggregate academic wages. The following two remarks show that these results hold in general.

Remark 3 *With an increasing potential value V of the final product, private research funding increases as a fraction of the academic budget.*

This remark is quite intuitive. If the potential value V increases, it should be switched to the private sector earlier in order not to risk success. Academia spends less time on the project, and the academic budget shrinks. Hence, the fraction of research funding increases.

Remark 4 *An increasing amount of research funding comes along with an increasing probability of marketability.*

Referring to 12, we have shown that I is an increasing function in q. Surprisingly, V itself has no direct influence on the absolute amount of I.

Proposition 1 *An increasing expected value of the final product comes along with either an increased fraction of research funding of the academic budget and/or an increased absolute amount of PRF.*

Proposition 1 combines Remarks 3 and 4 with the results we obtained until now. This is perfectly in line with fact 4 which suggests that the relative amount of research funds increases with the probability q that the final product is marketable. As mentioned in Remark 3, an increasing value V comes along with an earlier switching date t_s. In other words, an increasing value yields to earlier switching to the private sector and hence to reduced academic expenditures. A constant amount of research funds means therefore an increased fraction of research funds of the academic budget.

Proposition 2 *Research funding is never sufficient to cover the academic budget but increases with the commercialisable value.*

Note that, in addition to research funding, the academic sector can be financed when the research line is switched to the private sector at date t_s. For example, the research designer auctions off sell of the research line to a firm. Thus, Remark 3 does not imply that the academic sector is losing money and must be subsidized. However, research funding alone does not suffice to cover academic expenses but increases with a higher expected, respectively commercialisable value as often observed in sciences like engineering, biology or chemistry.

One important caveat is in order here. By looking at binding constraints (10) and (11), we have implicitly assumed that research funding is just large enough to incentivize the firm to gather information about the profitability of the project, but not larger. One could, of course, choose larger values for γ and I, as long as (10) holds and (11) binds. However, this would not enhance the profitability of the research line. In this case, research funding would unnecessarily shift money between firms and academia.

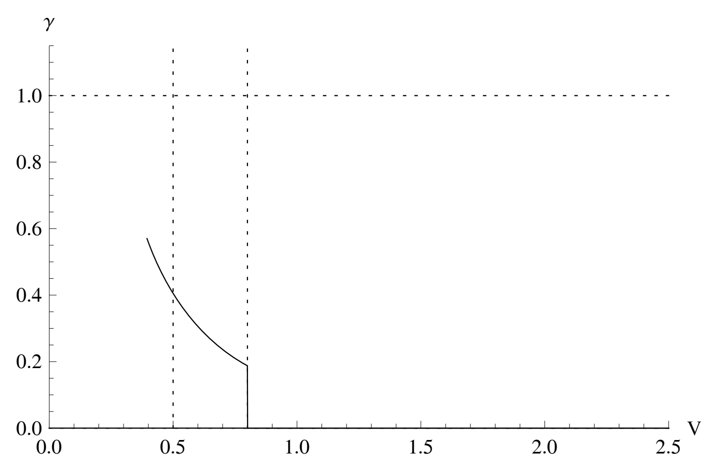
3.1 Public Research Funding

As a further variable, we can plot the fraction γ of the final product value that must be pledged to a firm that grants research funding. We have

$$\gamma = \frac{c}{q\,(1-q)\,V}\, e^{-\frac{\lambda\, c}{(1-q)\, w_a} - \frac{\lambda\, V + w_a - (\lambda\, T+1)\, w_p}{w_p}}. \tag{14}$$

This fraction γ could potentially exceed 100% for small values of V. As a consequence, private research funding would not work. Even pledging the complete final value V is insufficient to incentivize the firm to collect the crucial information c. However, we defined in section 2.2 the minimal V for research to be beneficial. This becomes clear in Figure 7. For large values of V, namely $V \geq 0.8$, there is no research funding at all, so $\gamma = 0$. This is in line with Figure 4. As you can see there, research projects are either transferred directly from academia to the private sector or are started as private projects right away. For smaller values ($0.8 \geq V \geq 0.39$), γ is positive, and it increases to $\gamma = 0.57$ as V falls for two reasons. First, only a smaller pie is shared in the end, so the firm must be promised a larger share γ for providing the PRF. Second, the project is turned private at a later date, putting the success of the research project at risk. For this, the firm must be compensated. At $V \leq 0.39$, the critical $\gamma = 0.57$ is reached. For even lower values V, no research projects are carried out.

Figure 7: Pledged Fraction γ of the Market Value V



4 Conclusion

Academia has a central feature which causes the main advantage compared to the private sector: scientific freedom. Researchers working within academia have the possibility to unfold themselves in creative scientific projects, which in turn decreases the potential to control their research agenda choices and choose the ways in which they allow others to build on their research discoveries (see Stern, 2004). In this paper, we develop a theoretical framework in which private research funding (PRF) transfers information about the value of a research project from the private sector into academia, in an incentive compatible way. We have placed the model in the context of prior work of Aghion, Dewatripont, and Stein (2008), who generated a discrete model accentuating the economic foundations of scientific freedom as being grounded in the granting of control rights to researchers. We have argued on the basis of the main findings of them, but focused rather on monetary arguments than on academic freedom in terms of intellectual property rights (IPR). As a consequence, this paper has provided predictions about the optimal sequence of research designs, about the optimal duration of a project within different designs.

Particularly, our model produces a number of qualitative and quantitative results. Following Remark 2 and in style of Figure 1, there is a total of six conceivable scenarios dependent on the value of a project, if one thinks of the valuation as a monetary variable. Projects typically start in pure academia, then obtain PRF, and finally are handed over to the private sector, where products reach marketability. Potentially, some of these steps are leapfrogged, but the order never changes. However, a project is never started with PRF right away. It is either initiated in the private sector, or in pure academia.

Furthermore, we can calculate the optimal date for inviting private money into academia (t_c), and the optimal date for completely switching to the private sector (t_s). Surprisingly and contrary to the public opinion, it could be suboptimal at all to get involved for private funding. In a sense, there is a period in which academia should be immune to market forces. We can also determine the fraction of the academic budget that is covered by private funding, finding that the budget is never covered completely. The absolute amount of PRF does not depend on the potential value of the product, but the switching date t_s is brought forward with an increasing value. Hence, the private sector does not finance research lines of limited value at all. It indirectly finances research lines of medium marketability.

In addition to the effects on the patterns of finance, the expected value ($q\,V$) impacts the amount of private research funds as well as the required consideration. An increasing expected value is attended by an increasing amount of research funds and with a decreasing requested fraction of the final value. This is consistent with our stylized facts we assessed. By providing data of funding in different fields of research, we suggested in Stylized Fact 4 that the relative amount of funds is positive correlated with the particular expected valuation of projects, in particular with the probability of marketability. By dint of the model, we can now explain, why some research projects are able to raise more research funds than others. That is to say a question of incentive compatibility. Because of profit-orientation, a firm only provides research funds if it is compensated for this effort to an adequate extent, which is assured in event of high monetary expectations. Hence, the approached applied research fields like medical or physical sciences, which produce obviously a high level of marketable output, are able to raise not only the vast bulk of research funds but also possess the major fraction of research funds regarding their total budget (see also Stylized Fact 4). Consistently, we detected that fields of less profitable research show fewer research fund fractions.

As a consequence, our results, mainly Remark 2 and Proposition 2 have strong implications for the organization of research. A possible policy maker should have in mind that basic research in terms of either improbably marketable or long-lasting research projects should almost always be subsidized by the government sector. The higher the expected value, the higher is the amount of acquirable PRF and less dependent is the researcher of public subsidies. Nevertheless, research projects incapable to gain PRF should not always be left in the lurch. These projects are primarily of basic character and therefore very important for subsequent research. Even though a quick marketable result does often not succeed directly, a mass of new research lines could arise from them. More applied research is traditionally privately supported to a greater extent or completely done in the private sector. So, it is first and foremost basic research (but definitely not solely) the policy maker should focus on regarding on the allocation of public funds. Moreover, we have shown that projects even supported by a great amount of PRF are still in need of further public funds.

In summary, if basic research suffers from financial problems due to the fact that the private sector cannot be incentivized to invest, also applied research is eventually hurt. In that case, the diversity of research would be reduced due to the fact that there would be only few (if at all) incentives to carry out basic or risky research. More applied and specialized projects would be carried out. Potentially, some research lines and at worst whole fields of research could become extinct.

A Appendix

Calculation of the minimal V: We give a lower limit for V, such that the project should be started in the first place. The algebraic expression depends on the research design. First, consider pure academic research, hence $t_s = T$. We need to check whether (1) remains positive with $t_s = T$, obtaining

$$V \geq \frac{(e^{\lambda T} - 1) w_a}{\lambda q}$$

No consider pure private research, hence $t_s = 0$. Then solving (1) for V,

$$V \geq \frac{T w_p}{q}$$

must hold, otherwise the project never starts. If there is switching, then $0 < t_s < T$, and

$$V \geq \frac{w_p(1 + \lambda\, T + \log(w_a/w_p)) - w_a}{\lambda\, q}.$$

This procedure can be used in the case of PRF. The conditions result from plugging the optimal dates t_s^* and t_c^* into (4),

$$\begin{aligned}\Pi &= q\,(1 - F(t_s^*))\left[V - w_p\,(T - t_s^*) - w_a\, t_s^*\right] - (1 - F(t_c^*))\, c \\ &- \int_0^{t_c^*} w_a\, t\, f(t)\, dt - q \int_{t_c^*}^{t_s^*} w_a\, t\, f(t)\, dt.\end{aligned}$$

and solving for V, respectively T. This yields

$$V \geq \frac{w_p \left(1 + \lambda\, T + \log\left(\frac{w_a + e^{\frac{\lambda\, c}{(q-1) w_a}} (q-1) w_a}{q\, w_p}\right)\right) - w_a}{\lambda}, \quad \text{or}$$

$$T \leq \frac{\lambda\, V + w_a - w_p(1 + \log(\frac{w_a + e^{\frac{\lambda\, c}{(q-1) w_a}} (q-1) w_a}{q\, w_p}))}{\lambda\, w_p},$$

respectively. ■

Proof of Remark 1: Assume the project in stage t, so the next stage is $t + dt$. Assume that v is the aggregated value of the remaining project, including the potential final V, and net of wages from $t + dt$ onwards. Hence, we concentrate on the period between t and $t + dt$ only, everything else is contained in v. If research is carried out in the private sector, the aggregate value is $v - dt\, w_p$. If carried out in academia, the according value is $(1 - \lambda\, dt)\, v - dt\, w_a$. Hence, there is a critical $\bar{v}$ such that research is better carried out in academia if and only if $v \leq \bar{v}$, given by

$$\bar{v} - dt\, w_p = (1 - \lambda\, dt)\, \bar{v} - dt\, w_a \implies \bar{v} = \frac{w_p - w_a}{\lambda}.$$

Now over time, v increases, because the time span $T - t$ decreases, such that less wages need to be paid until completion of the project. Consequently, if the research designer prefers private research at some stage, he prefers private research even more at a later stage. ■

Proof of Remark 2: The six possible regimes are caused by the combination of Remark 1, and equations (5) and (8). Referring to the calculations at the beginning of the Appendix, there is a ctitical value V. For lower values, research is not pursued because of beneficial reasons. As proofed in Remark 1, projects, once handed over to private research, will never return to academia. Deduced from (5), we have shown that $t_c > 0$. Therefore, the initial stage of a research project is carried out either in the academic or in the private sector, projects never start with PRF right away. Finally, consulting (8), we demonstrated that either $t_s \geq t_c$, so that there is scope for research funding before switching to private sector research, or $t_s = t_c$, and the project is directly transferred to the private sector. ■

Proof of Remark 3: Inserting the optimal switching dates and taking the derivative of B with respect to V yields

$$\frac{\partial B}{\partial V} = -q\,\frac{w_a}{w_p}\,e^{-1-\lambda\,T+\frac{w_a+\lambda\,V}{w_p}},$$

which is negative. However, research funding is

$$q\,(1-F(t_c))\,I = c\,\frac{q}{1-q}\,e^{-\frac{\lambda\,c}{(1-q)\,w_a}},$$

independent on V. As a direct consequence, research funding as a fraction of the academic budget is an increasing function. ■

Proof of Remark 4: Taking the derivative of I as computed in (12) with respect to c yields

$$\frac{\partial I}{\partial q} = \frac{c}{(1-q)^2} > 0.$$

■

Proof of Proposition 2: In Remark 3, we have already shown that the academic budget B is a falling function of V, whereas research funding is constant. Hence, in order to show that the former always exceeds the latter, it suffices to consider the maximal V for which there is research funding, as given by (8). For this V, the academic budget is

$$B = e^{-\frac{\lambda\,c}{(1-q)\,w_a}}\,\Big(\frac{w_a}{\lambda}\big(e^{\frac{\lambda\,c}{(1-q)\,w_a}}-1\big)-c\Big).$$

Some algebra shows that this term exceeds research funds if

$$\begin{aligned} B &\geq c\,\frac{q}{1-q}\,e^{-\frac{\lambda\,c}{(1-q)\,w_a}} \\ \iff \frac{w_a}{\lambda}\big(e^{\frac{\lambda\,c}{(1-q)\,w_a}}-1\big)-c &\geq c\,\frac{q}{1-q} \\ \iff \big(e^{\frac{\lambda\,c}{(1-q)\,w_a}}-1\big) &\geq \frac{\lambda}{w_a}\cdot\frac{c}{1-q}, \end{aligned}$$

which is always true because $e^x - 1 \geq x$ for all x, with equality only for $x = 0$. ■

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