The Equity vs. Royalty Dilemma in University Technology Transfer

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We develop a model, based on asymmetric information, which provides a rational explanation for the persistent use of royalties alongside equity in university technology transfer. The model shows how royalties, through their value destroying distortions, can act as a screening tool that allows a less informed principal, such as the university's Technology Transfer Office (TTO), to elicit private information from the more informed spinoffs. The model also generates other findings that are consistent with empirical observations. We show that when more experienced TTOs resort to contracts that include royalties, these are lower than those of less experienced TTOs. We also show that the empirically reported superior performance of equity only contracts is the result of selection bias; equity only contracts are designed for the higher value spinoffs. Finally, we use our modeling framework to assess the merits of a contract with variable royalties, sometimes used in practice. We show that such a contract is superior to contracts with non-variable royalties as it can act as a screening tool over a wider range of model parameters while causing fewer distortions.

Key words: university technology transfer; contract design; screening games

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1. Introduction

University spinoffs are entrepreneurial companies founded with the direct involvement of university graduates or faculty which aim to commercialize university generated ideas (Shane (2004)). These companies are formed on the back of academic research which is promising but not immediately commercializable. They aim to take the steps necessary - such as further development, prototyping, establishing manufacturing feasibility and improving the business plan - to convert an academic idea into a profitable set of products and services. To do so they usually require funding that goes beyond the financial resources of the founders. They raise this funding from public funds (Lerner (1999b), friends and family, private investors and Venture Capital (VC) firms (Lerner (1999a), Shane and Cable (2002)).

Since university based research, which after the Bayh-Dole act of 1980 is almost universally the property of the University (Mowery et al. (2002)), constitutes the intellectual backbone of the spinoffs, such companies are required to strike a licensing deal with the university's Technology Transfer Office (TTO). When granting the license the TTO aims to retain some of the value of the technology for the university. The terms of the licensing deal include royalty fees and equity stakes, as reported in a number of empirical (Feldman et al. (2002)) and survey studies (Bray and Lee (2000), Thursby et al. (2001)), and confirmed by the University TTOs we interviewed. Both royalty payments, which are a payoff for each unit sold, and equity stakes, which are a share of the (future) profits, are contingent payments in the sense that they depend on how well the company does in the future.

One of the best known examples of a university spinoff is Google, founded in 1998 by Larry Page and Sergey Brin, two Stanford PhD students, to commercialize their Page Rank algorithm for internet search. The now phenomenally successful internet giant at first raised money from angel investors and subsequently from VC funds and a public offering. Stanford University granted the exclusive license to Google to commercialize the Page Rank algorithm in exchange of an equity stake which it subsequently liquidated for $336M.[1] Stanford also receives annual royalties from Google, which in 2008 totalled $426,000 (GoogleDPS (2009)). Although Google was an exceptionally successful start-up, it is a typical example of how TTOs participate in the profits of their spinoffs. According to the STATT database, which collects comprehensive data from the Association of University Technology Managers' (AUTM's), of all US university TTOs reporting licensing income for the year 2009, 25.4% reported income from sales of equity stakes in addition to royalty income, up from 14.2% in 1996 when the survey started collecting income data.

The practical reasons behind the use of contingent payments such as equity and royalty, as opposed to upfront fixed fees for technology transfer, are understandable. Even start-ups with access to VC funding have limited financial resources which they try to stretch as far as possible. Furthermore, there are good theoretical reasons for having contingent payments. A number of models have demonstrated that there is a moral hazard problem that contingent payments might help to resolve, especially when university researchers who are not involved in the start-up need to provide effort. However, when comparing royalties to equity in these models it is generally accepted that equity Pareto dominates royalty for a simple reason. Royalties cause production distortions (Jensen and Thursby (2001)) and/or effort distortions (Crama et al. (2008)). The optimal spinoff production (or effort) is determined by equating marginal costs to marginal revenues. Royalties reduce marginal revenues and therefore distort the optimal production (or effort exerted). Equity does not have this problem as it offers a stake on profits and not just revenues. Since royalties

[1] http://www.redorbit.com/news/education/318480/stanford_earns_336_million_off_google_stock/ (last accessed on 18 Sep 2011)

appear to be Pareto dominated, the insistence of TTOs on continuing royalties alongside equity is a bit of a puzzle.

The use of royalty is even more puzzling as Bray and Lee (2000), who also identify a number of other benefits of equity over royalty, show that on average equity generates more value for the universities than royalties do. Feldman et al. (2002) attribute the reluctance to take on more equity over royalties to behavioural factors. TTOs are initially reluctant to experiment with new forms of payment such as equity stakes. However, as they become more experienced they tend to increase the proportion of equity deals in their licensing portfolio. Nevertheless, Feldman et al. (2002) find that even the most experienced universities continue to take on royalties.

Our paper provides a model of licensing based on asymmetric information that can explain the persistent use of royalties alongside equity in University technology transfer. The model assumes that the management of the spinoff, which as in Google's case could include the university faculty/students that invented then new technology, along with their VC backers, are more informed than the TTO about the market potential of the new technology. We use this model to identify the conditions under which it is optimal for the TTO to offer royalties alongside equities. Even though royalties distort value, we show that they can provide a screening mechanism that the TTO can use to extract information about the quality of the project. This prevents start-ups that have a higher probability of generating valuable products from extracting full information rents at the expense of the university. Indeed, under some conditions the TTO can extract all of the rents despite asymmetric information. Furthermore, we find that the optimal contract intended for start-ups with good quality projects contains lower (or even zero) royalties than the optimal contract offered to start-ups with poor quality projects. This result can be used to explain the empirical observation that equity deals on average generate more value for the university than royalty deals. It is a selection bias. It is not equity that generates the higher returns. It is high value projects that are better suited to equity contracts. Finally, we find that royalties are generally decreasing as the informational disadvantage of the TTO decreases. This finding is consistent with the empirical observation that more experienced TTOs use fewer royalties.

In addition to having descriptive value, our model provides a framework which can be used to assess the merits of alternative contractual structures. More specifically, we use our model to analyze an innovative contract that we have seen used in practice, namely equity with variable royalties (also described in Shane (2002)). Variable royalties are per unit payments that vary depending on the volume of sales the spinoff was able to generate. The simplest example of such variable royalties is that of royalty holidays, or per unit payments that have to be paid only if the start-up has reached a certain sales threshold. We show that contracts that include equity and variable royalties are superior to contracts with equity and constant royalties as they even more effective in screening while causing fewer distortions.

To summarize, our paper makes three contributions. Firstly, it contributes to the economics of licensing literature by developing a model of equity and royalty licensing. While the technology licensing literature which we review in the next section, has studied compensation structures that include fixed fees and royalties or fixed fees and equity it has not, to the best of our knowledge, studied the effect of combining the two in a single contract, nor has it examined the impact of variable royalties. Furthermore, our study is the first, to the best of our knowledge, that provides a rational explanation for the co-existence of royalty alongside equity in licensing deals. Second, the paper contributes to our understanding of university technology licensing by developing a normative model that has the power to explain empirical observations which until now were not well understood. Third, it provides a prescriptive framework that can be used to assess the merits of alternative contractual structures that are beginning to gain traction in practice, such as contracts with royalty holidays.

In the next section we present a review of the literature. Section 3 formulates a simple symmetric information model of technology licensing that demonstrates how royalties, as opposed to equity, destroy value through the distortion of production decisions. In Section 4 we introduce asymmetric information on the demand characteristics of the product and solve the optimal equity contract, equity-royalty contract, and contracts with equity and variable royalties. Section 5 presents an extensive numerical study which draws a number of interesting managerial conclusions, while Section 6 shows that our results are not affect by extending the model to include multiple spinoff types or moral hazard on behalf of the spinoff. Section 7 concludes.

Before we proceed it is worth noting that universities, for whom technology transfer is a pertinent issue, are far from being the only organizations interested in understanding how to best license technology. Research charities such as Cancer Research UK, a funding body for medical research in the UK, and private institutions such as the Cleveland Clinic, the leading cardiosurgery hospital in the US, have also created TTOs with similar mandates to University TTOs.[2] Furthermore, innovative companies such as IBM are also entering the technology transfer arena, be it with licensing agreements, start-up incubators or with open access arrangements. Our research is relevant to all of the above.

[2] `http://www.cancertechnology.com/about/who_we_are/`, `http://www.clevelandclinic.org/innovations/` (last accessed on 18 Sep 2011)

2. Literature Review

The economic impact of knowledge transfer from university research to industry, whether in the form of academic publications, consulting, transfer of patents, training of employees, creating innovative products or university brain drain, has long been on the agenda of the academic research (Agrawal and Henderson (2002), Cohen et al. (2002), Geiger (1988), Gibbons and Johnston (1974), Jaffe (1989), Nelson (2001), Rosenberg and Nelson (1994), Zucker et al. (2002), Toole and Czarnitzki (2010)). There has also been an increasing interest in the licensing of commercializable research breakthroughs and the creation of new firms - university spinoffs - as a consequence of these innovations (Di Gregorio and Shane (2003), Thursby and Thursby (2002), Jensen and Thursby (2001)). While this work is important in understanding university technology transfer and spinoff creation, this review will focus on the two strands of literature to which our paper makes a contribution: The literature on the economics of technology licensing and in particular as it applies to university licensing and the empirical literature on university technology transfer.

Early research on technology licensing finds that inventor rents are maximized by fixed fee, determined by auction (see Kamien (1992) for a survey). Contingent payments such as royalties are dominated by fixed fees because they distort production (Jensen and Thursby (2001)) or slow down adoption when network effects are important (Sun et al. (2004)). The use of royalties alongside fixed fees is justified in a principal agent framework by asymmetric information (Gallini and Wright (1990), Beggs (1992), Sen (2005b)) or moral hazard (Macho-Stadler et al. (1996), Choi (2001)), or both (Crama et al. (2008)). In these papers, the contingent nature of royalties turns them into either an information extraction mechanism (via signalling or screening) or a motivational device which better aligns the interests (and efforts) of both parties involved. Various other reasons for using royalties have also been identified. Erat et al. (2009) find that royalties should co-exist with fixed fees to moderate downstream competition among licensees, while Xiao and Xu (2009) show that subsequent renegotiation of royalties in exchange for fixed fees allows the realignment of incentives between a risk averse innovator and a risk neutral licensee.

Perhaps because these papers are motivated by licensing to established firms, they do not consider equity as viable means for technology transfer. In contrast, the modeling literature on university technology licensing examines equity explicitly. The main finding is that due to moral hazard problems some contingent payments are necessary, but in general equity is superior to royalties (Jensen and Thursby (2001), Dechenaux et al. (2009)). Since the superiority of equity over royalties is well established in literature, some papers chose to ignore royalties all together as viable means of technology transfer (Macho-Stadler et al. (2008)). Our paper is similar in spirit to the models of technology licensing under asymmetric information. For the main analysis, Sections 3-5, we abstract from the problem of moral hazard which we assume the start-up has resolved, and concentrate on the adverse selection problem which arises due to asymmetric information on the market potential. However we do check how our results are affected by incorporating moral hazard in Section 6. We build on the existing literature by studying contracts that include both equity and(fixed as well as variable) royalty. Our main contribution is to show that royalties can coexist alongside equity in equilibrium and they can be a helpful tool for a TTO that wants to extract more value from university innovation.

The empirical literature on university technology transfer shows that equity can be more profitable than fixed fee and royalties (Bray and Lee (2000)) because of a few jackpot start-ups that offer multimillion dollar returns. Even excluding these 'outliers', the authors find that equity returns are not lower than what the universities in their sample make from the more traditional fixed fee and royalties. Thursby et al. (2001) conduct a survey of the leading research universities in the US and find that 23% of all licenses include equity. Of the licenses that include equity, the authors find that 79% also include output based royalties. Feldman et al. (2002) report an increasing trend in the use of equity. Of the universities included in their survey only 40% had deals with equity in their portfolio in 1992. By 2000, this proportion had increased to 70%. Of all the licenses in their sample, they find that 14.4% include equity, but that this value varies drastically across universities, with one TTO having an equity element in 88.1% of its licenses. Feldman et al. (2002) present empirical evidence to show that it is the more experienced universities that are more likely to the use equity licensing. This is construed as evidence for the superiority of equity over royalties. It is argued that, with experience, universities will come to realize the benefits of equity deals and tend to adopt them more frequently.

The models developed in this paper allow us to provide alternative explanations for the above empirical observations. Firstly, our models show that the value from the use of royalties is not limited to the value gained directly from the cash flow generated by royalties but should also include the indirect value royalties generate through the reduction of information rents lost to VCs. The latter value is not easily measured and studies will inevitably underestimate the value of including royalties in contract offers. Secondly, we show that more valuable projects are best licensed with equity, lower value projects should be licensed by a combination of the two and the lowest value projects should be licensed with royalties only. This provides further explanation as to why royalties may appear to be less valuable than equity; selection bias. Thirdly, more experienced TTOs, who are less exposed to the problem of asymmetric information, are not harmed as much by the information rents enjoyed by spinoff when equity contracts are used, should indeed be more willing, than their inexperienced counterparts, to sign equity contracts. Lastly, the observation that, more often than not, royalties are used in conjunction with equity in licensing agreements is in line with the results of our theoretical models which suggest that equity only contracts are an option for only the best of projects which presumably make up a small proportion of the pool of projects available to a TTO.

3. Base Model: Symmetric information without uncertainty

University technology transfer is a complex process with multiple stakeholders, some of which might be driven by nonpecuniary motivations such as generating knowledge. We do not pretend to cover all of the complexities of this problem. Instead, we aim to demonstrate that if the spinoff has private information with regards to the potential market value of the technology, then it is optimal for the TTO to design contracts in which royalties coexist alongside equity despite their value distorting properties.

We begin the modeling section with a simple deterministic and symmetric information model that aims to demonstrate why equity contracts are, at least in theory, more attractive than royalty based contracts. Throughout the analysis, we follow the standard assumption of the technology licensing literature (Giebe and Wolfstetter (2008), Sen and Tauman (2007), Sen (2005a)) that the spinoff, upon successful completion of the technology, becomes a monopolist facing a linear inverse demand function for the new product $Q(P)$ given by $Q(P) = S - kP$, where S is the latent demand for the new product, P is the price per unit and k is a measure of how price sensitive consumers for this product are. Under the assumption that the new technology will allow the spinoff to act as a monopolist, the value of a self funded spinoff company that does not need to pay the TTO is given by $(P - c)Q(P) - C$, where c denotes the variable production costs and C denotes the fixed development cost that the spinoff will incur before it can commence production. These costs are appropriately adjusted to account for cost of capital and technical risk of the project. The value of the company is maximized at production level $Q = \frac{S-ck}{2}$ and it is equal to $\frac{(S-ck)^2}{4k}$.

In the context of the problem we are studying, the spinoff has to negotiate a licensing deal with the TTO which offers to retain a share $1-e$ in the spinoff in return for the exclusive license. The rest of the shares e will be kept by the spinoff and will be shared between any external funding bodies, such as Venture Capital funds. The value of the spinoff will be given by $e(P-c)Q(P)-C$, which is maximized when the production quantity Q is set to $Q = \frac{S-c}{2}$. The equity stake $(1-e)$ assigned to the TTO has no implications for the optimal production quantity; there is no production distortion. Furthermore, the sum of value to the spinoff and the TTO, is equal to the total value of the spinoff given by $Q(P-c)-C$.

An alternative to equity based technology transfer, favored by many TTOs is to opt for royalty based payments. These payments can be a fixed amount r per item sold or a percentage on total sales. For tractability purposes we take the former definition. The spinoff's value in a technology transfer contract that is based on such per item royalty payments is given by $(P-(c+r))Q(P)-C$, which is maximized when the production quantity Q is equal to $Q^* = \max\{0, \frac{S-ck-rk}{2}\}$. The optimal production quantity is non-increasing in the royalty rate r, hence there is production distortion. The value of the spinoff company with the royalty license, assuming $r \leq \frac{S}{k} - c$ is given by

$$\frac{{Q^*}^2}{k} = \frac{(S-(c+r)k)^2}{4k} \tag{1}$$

As we have shown, royalty based licenses have a distortional effect on the production decision of the spinoff. Since they increase variable costs, the spinoff that has to pay royalties will produce a smaller quantity and sell at a higher price than the equity based spinoff. To see how much value is lost by royalties we can subtract the total value under the royalty contract from the value under the equity contract. This gives $\Delta V(r) = \min\{k\left(\frac{r}{2}\right)^2, \frac{(S-ck)^2}{4k}\}$ which is always non-negative, indicating that the introduction of royalties reduces the total value created by the university innovation.

4. Information Asymmetry and Demand Uncertainty

The base model presented in the previous Section, although helpful for illustrating the distortional effects of royalties and pointing out how they can be circumvent by equity based contracts, it is clearly a simplification. In particular, it makes two assumptions that are hard to justify. Firstly, both the spinoff founders and the university know with certainty not only that the new technology will be successful but also what the demand is likely to be and also how price sensitive the demand is going to be. This is unlikely to be the case as university spinoffs are often commercializing new technology whose commercial potential is untested and hard to forecast. Secondly, both parties have full information on all project parameters. However, the TTO is unlikely to be able to appraise the market potential of a project with the same accuracy as the innovators of the technology or their experienced VC backers. As Shane and Stuart (2002) state “entrepreneurs are privy to more information about the prospects of their ventures and the abilities of and level of commitment of the founding team”. Furthermore, entrepreneurs have private information about the strength and composition of their social network which has been shown to be an important predictor of commercial success (Nicolaou and Birley (2003), Shane and Cable (2002)). In this Section we relax these two assumptions.

In order to model uncertainty in market valuation in a simple way, we assume that the inverse demand function for the finished product will turn out to be either of type h with probability θ_i or of type l with probability $1-\theta_i$, with the inverse demand given by $Q = S_j - k_j P$ where $j \in \{h, l\}$. In order for our results to be as general as possible we will investigate both possible scenarios with regards to the parameters S_i and k_i. Namely, we will allow for $S_h \geq S_l$ and $k_h \geq k_l$, which corresponds to the situation where the project has the possibility of addressing either a large but price sensitive market, or a smaller but less price sensitive market, or $S_h \geq S_l$ and $k_h < k_l$ which

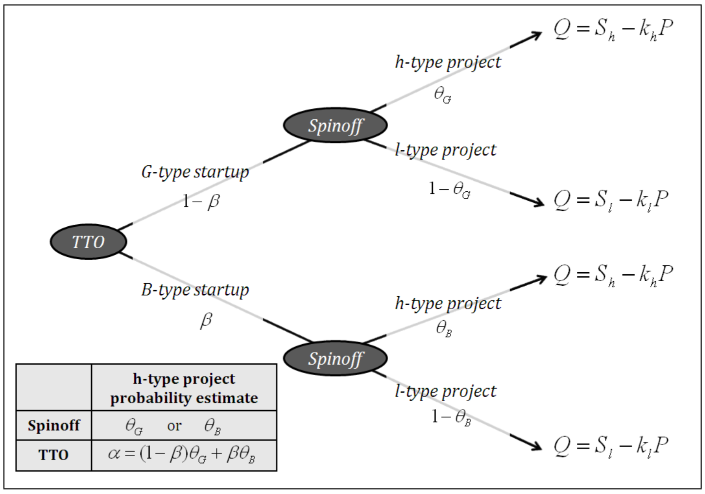


Figure 1 **Information Structure**

corresponds to the situation where the end product will address either a larger market that is not very price sensitive or a smaller and more price sensitive market.[3] Furthermore, we restrict the range of the parameters S_i and k_i such that the value of the h type is higher than that of l. This implies that $\frac{(S_h - ck_h)^2}{k_h^2} > \frac{(S_l - ck_l)^2}{k_l^2}$. This formulation is a first step in capturing the nature of early stage innovation, such as those typically licensed by universities, whose demand is difficult if not impossible to predict with 100% accuracy.

To capture the fact that the management of the spinoff is likely to be better informed than the TTO about the potential demand characteristics, we assume that the spinoffs can be of either type B or type G. Spinoffs of type G have a higher probability, θ_G, of generating projects of type h than spinoffs of type B do (i.e. $\theta_B < \theta_G$). To introduce information asymmetry we assume that the spinoff management knows its type, i.e. it knows the probability θ_i, $i \in \{G, B\}$, while the TTO does not know the type. Instead, the TTO believes the spinoff to be of type G with probability $1 - \beta$ and B with probability β. The information structure is summarized in figure (1).

It is perhaps helpful to think of the setting as follows. The TTO has a belief about the probability of a project being of type h which is $\alpha = \beta\theta_B + (1 - \beta)\theta_G$ and of type l with probability $1 - \alpha = 1 - \beta\theta_B - (1 - \beta)\theta_G$. This belief, although true on expectation for any given project, it does not take into account some spinoff specific information which the management is in a position to hold. Using this information, the management can resolve some, but not all, of the uncertainty and is able to establish more accurately whether the project is of type h or type l. The TTO knows that the spinoff has superior information, and it also knows that it will use this information to deem the market potential to be of type G with probability $1 - \beta$ or B with probability β.

[3] The scenarios where $S_h < S_l$ and $k_h \leq k_l$ or $S_h < S_l$ and $k_h > k_l$ correspond to relabeling the scenarios already covered.

Note that both the spinoff of type G as well as that of type B have the potential of generating projects of type h or l. They only differ in the probability of generating such as scenario. This specification renders impossible to verify the type of spinoff, even if the demand is observable and verifiable ex-post. After all, a G-type spinoff can always claim to be a B-type and if the project turns out to be of type h it can always claim to have been lucky. This inherent uncertainty in the demand of the finished end product, which allows the spinoff to mask its true type even ex-post, has an impact on the types of contracts that can be implemented. More specifically, the non-verifiability of project type renders the TTO unable to offer spinoff type dependent contracts. Nevertheless, since demand is verifiable, the TTO could potentially offer demand dependent contracts.

In our study, we will first focus on equity only and then equity with fixed royalty contracts (that are not demand dependent). We will then examine equity with demand dependent royalty contracts. While it is theoretically possible to offer demand dependent equity, such equity would be difficult to implement in practice. This is because any equity shares are agreed upon at the time the contract is signed, which is typically a few years before demand is realized. Once demand is realized, there is no mechanism to readily change the equity holdings of the TTO. In contrast, it is much easier to set demand based royalties. These can be generated by variable royalties, or royalty holidays, and have been used in the license agreements of some TTOs (Shane (2002)). We also refrain from analyzing other, more complicated, contractual structures as our primary goal is to provide a description of what is observed in practice. More formally, the set of possible contracts offered by the TTO is given by $(e, r(Q))$ where e is the equity offered upfront and $r(Q)$ is the output dependent royalty.

4.1. Equity and fixed royalty contracts

In this Section we limit our attention to contracts that do not depend on the demand realization. These contracts belong in the set given by (e, r) where e is the equity stake offered to the spinoff and r is the royalty per quantity produced payable to the TTO. Under such a contract, the expected value of the VC backed company of type $i \in \{G, B\}$, excluding development costs C is given by $\pi_i(r) = \theta_i V_h(r) + (1 - \theta_i) V_l(r)$ where $V_j(r)$ with $j \in \{h, l\}$ is the value of the new company that has to pay royalties r per item produced, given that the inverse demand function is $Q = S_j - k_j P$ and the VC backed venture makes an optimal production decision $Q_j^*(r) = \max\{0, \frac{S_j - ck_j - rk_j}{2}\}$. As shown in equation (1), the value is given by $V_j(r) = \frac{Q_j^{*2}}{k_j}$. The value to the TTO when the project is of type $i \in \{G, B\}$ is given by $U_i(e, r) = (1 - e)\pi_i(r) + r\left[\theta_i Q_h^*(r) + (1 - \theta_i) Q_l^*(r)\right]$. The first term is the expected value of the TTOs equity share while the second is the expected cashflow from royalties. As at the time the contract is signed the TTO only know the type of project in distribution, the expected value of TTO over the possible project types is given by

$$U(e, r) = \beta U_B(e, r) + (1 - \beta) U_G(e, r)$$

$$= (1-e)\left(\alpha V_h(r) + (1-\alpha)V_l(r)\right) + r\left(\alpha Q_h^*(r) + (1-\alpha)Q_l^*(r)\right),$$

where $\alpha = (1-\beta)\theta_B + \beta\theta_G$ is the TTOs assessment of the probability of the project is of type h.

When information about the project type at the time the contract is singed is common knowledge, the TTO can extract all rents simply by setting the royalty to zero to avoid distortions and set a type dependent equity that is high enough to allow the spinoff to recoup its investment costs but no more than that:

$$e_G = \frac{C}{\pi_G(0)} = \frac{4C}{\theta_G\frac{(S_h-ck_h)^2}{k_h} + (1-\theta_G)\frac{(S_l-ck_l)^2}{k_l}},\; e_B = \frac{C}{\pi_B(0)} = \frac{4C}{\theta_B\frac{(S_h-ck_h)^2}{k_h} + (1-\theta_B)\frac{(S_l-ck_l)^2}{k_l}}$$

4.1.1. Equity contract: A pooling equilibrium Under asymmetric information and demand uncertainty, if the TTO was to offer the two contracts described above, the G-type spinoff would always pretend to be of B type, thus appropriating all informational rents. The TTO is left with two options, either offer e_B and allow the commercialization of both types of projects at the expense of giving up all informational rents to the G-type spinoff, or offer e_G and appropriate all rents from the G-type but at the expense of preventing further commercialization by B-types. Which of the two is more preferable will depend on whether the difference of value between type G and type B spinoffs is greater than the value of type B spinoffs, appropriately adjusted for how likely a spinoff of type G vs a type B is. The exact value is summarized in the proposition below whose proof is simple and we omit for brevity.

Proposition 1. *The optimal equity only contract is given by*

$$e = \begin{cases} \frac{C}{\pi_B(0)} = \frac{4C}{\theta_B\frac{(S_h-ck_h)^2}{k_h}+(1-\theta_B)\frac{(S_l-ck_l)^2}{k_l}} & \text{if } (1-\beta)C\left(\frac{\pi_G(0)}{\pi_B(0)}-1\right) < \beta(\pi_B(0)-C) \\ \frac{C}{\pi_G(0)} = \frac{4C}{\theta_G\frac{(S_h-ck_h)^2}{k_h}+(1-\theta_G)\frac{(S_l-ck_l)^2}{k_l}} & \text{if } (1-\beta)C\left(\frac{\pi_G(0)}{\pi_B(0)}-1\right) \geq \beta(\pi_B(0)-C). \end{cases}$$

The only feature differentiating the two types of spinoffs is the probability of high (θ_G) or low (θ_B) demand. Since there is no element of the contract that can be made contingent on the demand realized, there is no way for the TTO to offer a contract that would differentiate between the two types. Assuming that the TTO wants to license technology for both types of spinoffs, the best she can do is to offer a contract that binds the individual rationality constraint of the B-type. The TTO then offers the same contract to the G-type as offering a higher equity stake would lower its own expected payoff while offering a lower equity stake would make it preferable for the G-type to accept the contract designed for the B-type. The excess equity that the G-type receives generates the positive information rents. Alternatively, the TTO might decide to offer the higher equity stake that extracts all of the rents from the G-type spinoff at the expense of excluding the B-type from licensing university technology. Since university TTO have a number of other objectives besides purely maximizing profit (Feldman et al. (2002)), it is unlikely that they would be purposely preventing viable technology from being licenced. However, we have to point out that in equilibrium, this might be the optimal behavior.

4.1.2. Equity and royalty contract: A separating equilibrium Since an equity only contract does not allow the TTO to license technology to both spinoff types without giving up all information rents, it is worth investigating if a joint equity and royalty contract can fare better. Here we focus on separating equilibria, that allow the TTO to license to both types. Appealing to the revelation principle (Myerson (1979)), and without loss of generality, we will assume that the TTO offers two contracts (e_G, r_G) and (e_B, r_B), the first intended for the G-type and the second for B-type spinoff. The TTO will choose contracts such that

$$\max_{e_G, e_B, r_G, r_B} U = (1-\beta)U_G(e_G, r_G) + \beta U_B(e_B, r_B) \quad (2)$$

such that

$$e_G \pi_G(r_G) \geq e_B \pi_G(r_B), \quad \text{ICG} \quad (3)$$

$$e_B \pi_B(r_B) \geq e_G \pi_B(r_G), \quad \text{ICB} \quad (4)$$

$$e_G \pi_G(r_G) \geq C, \quad \text{IRG} \quad (5)$$

$$e_B \pi_B(r_B) \geq C, \quad \text{IRB} \quad (6)$$

$$0 \leq e_B, e_G \leq 1, \ r_B, r_G \geq 0,$$

with $U_i(e,r) = (1-e)\pi_i(r) + r\,[\theta_i Q_h^*(r) + (1-\theta_i)Q_l^*(r)]$. The first two constrains, often referred to as incentive compatibility constraints ensure that a spinoff of type G will prefer the equity-royalty allocation designed for type G over that designed for type B and vice versa. The next two constraints, often called individual rationality or participation constraints, ensure that both types of spinoffs receive a nonnegative expected payoff. Subject to these constraints, the TTO would like to maximize its own payoff from the licensing agreement. It is worth noting that we limit the royalties to be positive as we do not want to consider contracts where the university subsidizes VC backed spinoffs. Such contracts are not observed in practice as universities have limited financial resources (Lockett and Wright (2005)).

Proposition 2. *Under fixed royalty contracts, a separating equilibrium exists if and only if the following condition is satisfied*

$$\frac{S_h}{k_h} - \frac{S_l}{k_l} < 0, \quad (7)$$

and is characterized by

$$r_B = \min\{\underline{r}, r^*, \overline{r}\}, \quad e_B = \frac{C}{\pi_B(r_B)},$$

$$r_G = 0, \quad e_G = e_B \frac{\pi_G(r_B)}{\pi_G(0)} = \frac{C\pi_G(r_B)}{\pi_B(r_B)\pi_G(0)},$$

where r^* is the root of the equation

$$r\beta\left(\theta_B k_h + (1-\theta_B)k_l\right) = -(1-\beta)C\frac{\theta_G-\theta_B}{(\pi_B(r))^2}\frac{S_l-k_l(c+r)}{2}\frac{S_h-k_h(c+r)}{2}\left(\frac{S_h}{k_h}-\frac{S_l}{k_l}\right), \tag{8}$$

$$\underline{r} = \frac{\frac{S_h}{\sqrt{k_h}}-\frac{S_l}{\sqrt{k_l}}}{\sqrt{k_h}-\sqrt{k_l}} - c$$

and $\overline{r}$ is the unique solution of the equation $\pi_B(r) = C$.

What Proposition 2 shows is that when the demand of the h-type project is sufficiently more price sensitive than that of the l-type project, then royalties can coexist with equities. In this case the TTO can extract information from the more informed spinoff by offering two contracts, one with lower equity and no royalties intended for the G type and one with higher equity and high enough royalties intended for the B type.

To understand the intuition behind this results it is important to emphasize that royalties have an asymmetric impact on the two types of spinoffs. When demand for the h-type project is sufficiently more price sensitive than the l-type project (as implied by equation (7)), the value destroyed by royalties is greater for projects of type h than that of type l. Therefore the value lost due to royalty distortions is greater for the G-type spinoff that has a higher probability of having a project of type h. If this asymmetric distortion is large enough (i.e. equation (7) is satisfied), it can be exploited by the TTO to increase its payoff compared to the equity only case where both types are offered the equity that makes the participation constraint of the B-type binding. It can do so by adding a small fraction ϵ of royalties to the contract intended for the B-type and at the same time increase the B-type's equity stake just enough so that the participation constraint is still binding. The G-type will not want to pretend that he is of B-type in order to get the higher equity stake as the royalties would harm him more than the B-type and the extra equity allocated to the B-type will not be enough to cover the loss of the G-type. In fact, since royalties are so undesirable for the G-type, the TTO can decrease the equity stake of the G-type by a little as well. The TTO can continue adding royalties and increasing the equity stake of the B-type and at the same time decreasing the equity stake of the G type until one of the following things happens. Either it extracts all of the rents from the G-type in which case there is no need to continue increasing royalties ($r_B = \underline{r}$), or until the equity allocated to the B-type has reached 100% and therefore it cannot increase the royalty and equity offering any further ($r_B = \overline{r}$), or finally when it reaches a point where the value destroyed by royalties is higher than the value added by decreasing the stake of the G-type ($r_B = r^*$).

It is worth making a few observations here. First, equation (7) is a single crossing condition of the type frequently encountered in information economics (see for example Bolton and Dewatripont (2005), page 54) and it implies that the project under development will serve one of two possible demand types: Either a relatively large but price sensitive market or a relatively small niche market where demand is sufficiently less price sensitive than in the mass market. These market types are closely related to what Johnson and Myatt (2006) show to be optimal for a firm designing new products to follow depending on demand dispersion. When dispersion is high, i.e. consumers' valuations are relatively heterogeneous, the firm should design a "love-it-or-hate-it" type of product and pursue a relatively small but price insensitive set of consumers. When dispersion is low, and a large proportion of customers place similar value on the product, it is optimal to pursue a mass market strategy which will naturally be more price sensitive.

Second, we find that there exist start-ups of sufficiently low value (B-type) for which it is optimal for the TTO to retain no equity and instead license the technology with royalty (equal to $\overline{r}$) only. This is consistent with the empirical observation that some spinoffs license technology exclusively through royalties without the TTO having any equity participation.

Third, we find that sufficiently high value (G-type) spinoffs, that have a higher probability of producing a more valuable product, are offered a contract with zero royalties. This is consistent with the observation that on average, equity licensing is generating a higher revenue for the TTO than royalty licensing. However, what Proposition 2 shows is that this effect is not because equity is an inherently better way of licensing university technology, it is rather a selection bias: technology that is more likely to generate high value products is more likely to be licensed with equity.

4.2. Equity and variable royalties contract

Having investigated the properties of an equity-royalty contract, we apply the framework developed in the previous Sections to analyze the properties of a more complicated contract that uses variable, demand depended, royalties alongside equity. Under this setting the TTO can therefore offer two licenses, one with parameters e_G, r_{Gl} and r_{Gh} intended for the spinoff of type G and another with e_B, r_{Bl} and r_{Bh} intended for the spinoff of type B. Under such a contract, the expected value of the VC backed company of type $i \in \{G, B\}$, excluding development costs C is given by

$$\pi_i(r_{jl}, r_{jh}) = \theta_i V_h(r_{jh}) + (1 - \theta_i) V_l(r_{jl}),$$

with $V_h(r)$ and $V_l(r)$ are given by equation (1).

The TTO has to solve the following constrained optimization problem (9) under two incentive compatibility constraints and two individual rationality constraints.

$$\max_{e_G, e_B, r_{Gh}, r_{Gl}, r_{Bh}, r_{Bl}} \quad U = (1-\beta) U_G(e_G, r_{Gh}, r_{Gh}) + \beta U_B(e_B, r_{Bl}, r_{Bh}) \tag{9}$$

such that

$$e_G \pi_G(r_{Gl}, r_{Gh}) \geq e_B \pi_G(r_{Bl}, r_{Bh}) \tag{10}$$

$$e_B\pi_B(r_{Bl},r_{Bh}) \geq e_G\pi_B(r_{Gl},r_{Gh}) \tag{11}$$

$$e_G\pi_G(r_{Gl},r_{Gh}) \geq C \tag{12}$$

$$e_B\pi_B(r_{Bl},r_{Gh}) \geq C, \tag{13}$$

$$0 \leq e_G, e_B \leq 1,\ r_{Gh}, r_{Gl}, r_{Bh}, r_{Bl} \geq 0$$

with $U_i(e_j,r_{jl},r_{jh}) = (1-e_j)\pi_i(r_{jl},r_{jh}) + \left[\theta_i r_{jh}\frac{S_h - ck_h - r_{jh}k_h}{2} + (1-\theta_i)r_{jl}\frac{S_l - ck_l - r_{jl}k_l}{2}\right]$.

Proposition 3. *Under equity and variable royalty contracts there always exists a separating equilibrium. It is optimal for the TTO to offer two contracts, one intended for the B-type spinoff with*

$$e_B = \frac{C}{\pi_B(0,r_{Bh})},\ r_{Bh} = \min\{r^*, \overline{r}, \underline{r}\},\ r_{BL} = 0$$

where r^* is the unique root of the equation

$$(1-\beta)e_B(0,r_{Bh})Q_h(r_{Bh})(\theta_G - \theta_B)\frac{V_l(0)}{\pi_B(0,r_{Bh})} - \frac{1}{2}\beta\theta_B k_h r_{Bh} = 0,$$

$$\overline{r} = \frac{S_h - ck_h}{k_h} - \sqrt{\left[C - (1-\theta_B)\frac{(S_l - ck_l)^2}{4k_l}\right]\frac{4}{k_h\theta_B}},\ \underline{r} = \frac{S_h - ck_h}{k_h} - \frac{(S_l - c)}{\sqrt{k_h k_l}}$$

and one intended for the G-type spinoff with $e_G = e_B\frac{\pi_G(0,r_{Bh})}{\pi_G(0,0)}$, $r_{Gh} = 0$, $r_{Gl} = 0$

Proposition 3 shows that variable royalties, in contrast to fixed royalties, can induce a separating equilibrium for any model parameters. To understand the intuition behind this result let us revisit the intuition behind the fixed royalty result of Proposition 2. Fixed royalties are charged at the same rate regardless of the realized demand. In order for them to generate the asymmetric impact necessary to allow type separation, these fixed royalties need to be coupled with a different demand price sensitivity in each of the h-type and l-type demand scenarios. For variable royalties, this asymmetric impact is already present as the probability of h-type demand scenario differs across the types. This difference alone (i.e. not coupled with price sensitivity) is enough to create the required asymmetric effect. Thus variable royalties can be used as a screening tool regardless of model parameters, and therefore have wider applicability.

Furthermore, Proposition 3 also shows that it is optimal to charge royalties that are non-decreasing in project type value. Charging zero royalties for the least valuable projects turns out to be the most cost effective way to ensure the asymmetric impact of royalties on different types while destroying as little value as possible. The TTO can design contracts such that the B-type self selects a contract with relatively high equity and royalties payable only when the technology turns out to be of the more valuable h-type project, while the G-type selects a contract with relatively low equity and no royalties. Similar to the case of the fixed royalties of Proposition 2, the

	Parameters Used	Parameters Varied
Figure 2	$\theta_G = 0.85, \theta_B = 0.15$ $k_h = 1.4,\ k_l = 0.4$ $c = 2,\ C = 8$ $S_0 = 14$	$\Delta_S \in \{\underline{\Delta_S}, \overline{\Delta_S}\}$, steps of 0.05 $\beta \in \{0.005, 0.995\}$, steps of 0.005
Figure 3	$\theta_G = 0.75, \theta_B = 0.25$ $\beta = 0.5,\ k_0 = 1.5$ $c = 2,\ C = 8$ $S_0 = 14$	$\Delta_S \in \{\underline{\Delta_S}, \overline{\Delta_S}\}$, steps of 0.05 $\Delta_k \in \{0.01, 0.99\}$, steps of 0.01
Figure 4a	$S_h = 21.5,\ S_l = 6.5$ $\beta = 0.15,\ \theta_0 = 0.5$ $k_h = 1.4,\ k_l = 0.4$ $c = 2,\ C = 8$	$\Delta_\theta \in \{0.01, 0.49\}$, steps of 0.01
Figure 4b	$S_h = 19.8,\ S_l = 8.2$ $\beta = 0.15\ ,\ \theta_0 = 0.5$ $k_h = 1.4,\ k_l = 0.4$ $c = 2,\ C = 8$	$\Delta_\theta \in \{0.01, 0.49\}$, steps of 0.01

Table 1 Table of Parameters

optimal royalties for the h-type of project, are the minimum of three values $(\underline{r}, \overline{r}, r^*)$. The first $(\underline{r})$ corresponds the royalties that allow the TTO to extract all of the rent from the G-type, the second $(\overline{r})$ correspond to the case where the equity allocated to the B type has reached 100% and the third (r^*) correspond to the case where any further increase in royalties would destroy more value than the TTO can extract by decreasing the equity allocated to the G type.

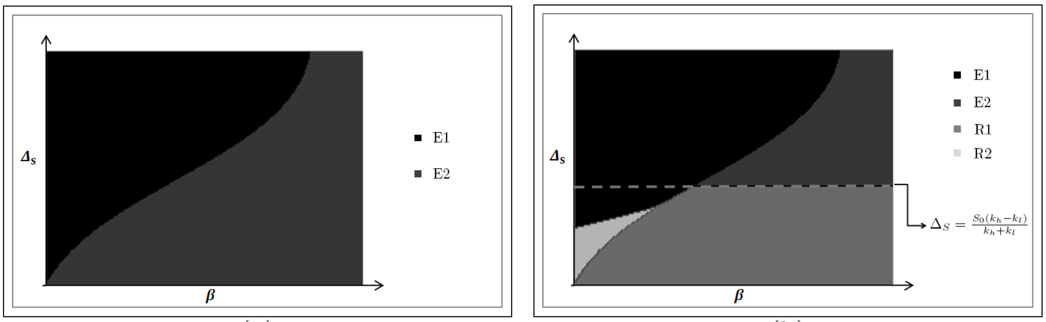
It is worth noting that although demand variable royalties are more complicated to implement, they are being used in practice. One TTO we have interviewed regularly signs equity transfer deals where it agrees to forego royalties until a certain threshold level of sales has been reached.

5. Numerical Investigation

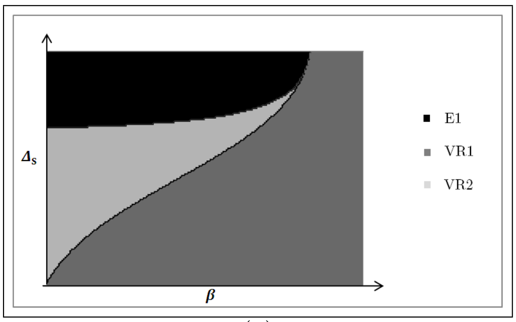
In order to gain better intuition and understand how the contracts we examined in the previous Sections are optimally deployed we perform a detailed numerical analysis. We vary the proportion of B-type spinoffs (β) in the population, the gap between high or low latent demand $(2\Delta_S = S_h - S_l)$, the gap between price sensitivity of h-type and l-type projects $(2\Delta_k = k_h - k_l)$ and the severity of informational asymmetry problem $(2\Delta_\theta = \theta_G - \theta_B)$ changes. The gap between high and low latent demand is characterized by Δ_S, by setting a nominal level S_0 and setting $S_h = S_0 + \Delta_S$ and $S_l = S_0 - \Delta_S$.[4] The pairs, $\{k_0,\ \Delta_k\}$ and $\{\theta_0,\ \Delta_\theta\}$ are defined similarly. We present the results in figures 2 through 4. A summary of all parameters used in the figures of this Section is given in table 1.

Figure 2a depicts the two regions of proposition 1: The TTO can offer the relatively high equity stake that binds the participation constraint of the B-type startup, license to both types of spinoffs

[4] We vary Δ_S, from $\underline{\Delta_S} = \frac{(S_0 - ck_l)\sqrt{k_h} - \sqrt{k_l}(S_0 - ck_h)}{\sqrt{k_l} + \sqrt{k_h}}$ to $\overline{\Delta_S} = \frac{S_0(k_h - \theta_B(k_h + k_l)) - ck_h k_l(1 - 2\theta_B)}{k_h - \theta_B(k_h - k_l)}$. The lower bound on Δ_S ensures that l-type projects are inherently less valuable than h-type projects. The upper bound ensures that the expected value of the B-type spinoff is monotonically decreasing in Δ_S.



(a) (b)



(c)

Label	Contract Details
E1	Equity contract: B-type is excluded
E2	Equity pooling contract: G-type enjoys positive rents
R1	Equity, Royalty contract: Types would be pooled with equity only contracts
R2	Equity, Royalty contract: B-types would be excluded with equity only contracts
VR1	Equity, Variable Royalty contract Types would be pooled with equity only contracts
VR2	Equity, Variable Royalty contract B-types would be excluded with equity only contracts

(d)

Figure 2 Contract Regions and Abbreviations

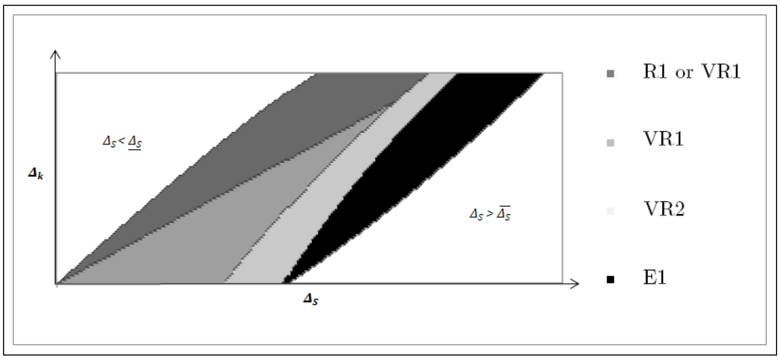


Figure 3 Contract Regions: Both Fixed and Variable Royalties

with positive information rents for the G-type (region E2). Alternatively, the TTO can offer the relatively low equity stake that binds the participation constraint of the G-type; which leaves no information rents to the G-type but all value from the B-type spinoff is lost because the technology is not licensed (region E1).

As shown in Proposition 2, when the h-type product is facing a sufficiently more price-sensitive set of consumers compared to the l-type product, the distortional effect of royalties is sufficiently more pronounced for the G-type spinoff than the B-type spinoff. Thus a separating equilibrium can exists, provided (7), which can be written as $\Delta_S < \frac{S_0(k_h-k_l)}{k_l+k_h}$ and is shown in figure 2b by the dashed horizontal line. The black (E1) and dark grey (E2) regions are defined as in the previous paragraph. The two lighter shades of grey (R1 and R2) correspond to regions where the TTO offers a menu of contracts; one with equity and royalty intended for the B-type spinoff and the other with equity only intended for the G-type. The two shades of light grey distinguish between the cases where, with equity only contracts, the TTO would have preferred the pooling equilibrium (R1) and the case where it would have been financially optimal not to license to B-types at all (R2).

Proposition 3 shows that the use of variable royalties, that are only invoked when the project turns out to be of type h, also allow the TTO to design contracts that lead to separating equilibria which we illustrate in figure 2c. When β is close to 0, very high values of Δ_S make it optimal for the TTO not to license at all to B-types (region E1). In all other areas of the figure the TTO opts for the variable royalties induced separating equilibrium, sometimes replacing the pooling equilibrium of the equity only contract (region VR1), at other times replacing the contract excluding the B-types (region VR2).

Figure 3 demonstrates the wider applicability of the variable royalty contract compared to the fixed royalty contract. For lower Δ_k values, the impact of price on the demand of h- and l-type projects is similar, while for high Δ_k the impact of price on the demand of h-type projects is much higher than the impact on the demand of l-type projects. Figure 3 shows that fixed royalties are not an effective screening tool for low Δ_k values but are effective over a wider range of Δ_S values when Δ_k is large (region R1). Variable royalties lead to a separating equilibrium in all shades of grey (regions R1, VR1 and VR2) while fixed rate royalties are effective only in the darkest shade (R1).

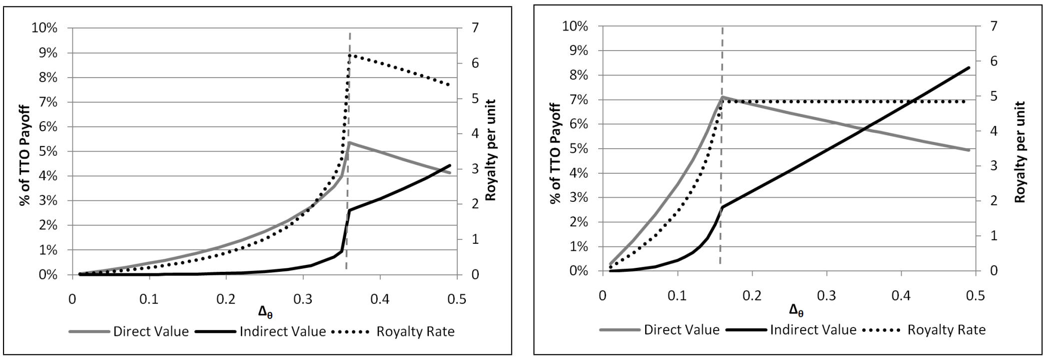
The contract region plots of figures 2 and 3 generated by our numerical study allow us to make several observations that were not immediately obvious from Propositions 2 and 3:

1. For some parameter values, the use of royalties with equity permits the licensing of technology to B-type spinoffs that otherwise would have been optimal to exclude. In this region (R2 or VR2), while royalties may still be regarded as inefficient from a production decision perspective, they may be dubbed welfare improving from a system perspective.

2. The use of variable royalties with equity permits the licensing of technology to B-type spinoffs that otherwise would have been optimal to exclude not only in pure equity contracts but also in equity-fixed royalty contracts. Thus, variable royalty contracts are welfare improving over a wider range of parameter values (VR2 larger than R2).

3. It may be the case that the TTO is better off excluding B-type spinoffs even when it is possible to extract information using either fixed or variable royalties. This area (E1) is much smaller for variable royalties (figure 2c) than the corresponding area for fixed royalties (figure 2b).

4. As Δ_k decreases, fixed royalties become a less effective screening tool in that they lead to a separating equilibrium over a much narrower range of Δ_S values (see region R1 in figure 3).



(a) (b)

Figure 4 Effect of Information Asymmetry on Royalties

We now take a closer look at the optimal (per unit) royalty rate charged by the TTO. In doing so, we want to observe what effect the severity of the asymmetric information problem (Δ_θ) has on the royalty rate charged and on the value extracted by this royalty. In figures 4a and 4b the dotted lines show royalty rates charged which can be read off the secondary y-axes.[5] Barring the case where the TTO takes no equity in the B-type spinoff, it can be seen from both 4a and 4b that royalties charged (dotted black line) are non-decreasing in Δ_θ. This finding, that royalty levels are non-decreasing in Δ_θ, which we have found to hold for all parameter values of our numerical study, is consistent with the empirical observation that more experienced TTOs use less royalties. This is not just because more experienced universities are more likely to produce spinoffs of high quality, it is also because such universities are in a better position to assess the potential value of their start-ups and thus need to rely less on royalties as a screening mechanism.

Furthermore, in figures 4a and 4b the solid lines represent the total value appropriated by the TTO that is attributed to royalties, which can be read off the primary y-axes. The grey line shows the expected value generated directly by royalties ($\beta r_B\,(\theta_B Q_h(r_B) + (1-\theta_B)Q_l(r_B))$) while the solid black line gives the indirect value generated by royalties; defined as the excess value extracted from the G-type spinoff, when compared to the pooling equilibrium of proposition 1. A large proportion of the value generated by royalties is indirect. In fact, when the asymmetric information problem is severe, most of the value of royalties is indirect. This indirect value of royalties is not readily observable and empirical studies inevitably underestimate the value generated by royalties.

[5] Recall that the optimal royalties charged to the B type spinoff are the minimum of $\{\underline{r}, r^*, \overline{r}\}$. In figure 4a, the vertical dashed line indicates the point beyond which the value of the B-type spinoff is so low that in order to discourage the G-type from choosing the contract intended for the B-type, the TTO takes no equity stake in the B-type and charges a royalty rate $\overline{r}$. To the left of the vertical line, the TTO charges r^*. Similarly, in figure 4b, to the right of the vertical dashed line the TTO charges $\underline{r}$ while to the left, it charges r^*.

6. Model Extensions

As a robustness check we develop numerical models that check whether the results of the adverse selection model follow through when moral hazard on behalf of the spinoff is added to the model and when we allow for more than two types of spinoffs. The extensions indicate that the results of the original model are indeed robust to these alternative specifications.

6.1. Moral Hazard

Moral hazard is typically modeled by assuming that the agent's payoff function is concave in effort, i.e. there are diminishing returns to effort (e.g. Crama et al. (2008), Plambeck and Taylor (2006), Xiao and Xu (2009)). To do this in our model we introduce an endogenous probability of technical success $p(f)$ that depends on costly, unobservable and/or unverifiable effort f by the spinoff's management. To simplify the analysis we employ a specific functional form for the probability of success. We assume it is given by $p(f_i) = 1 - \exp(-f_i)$, which is increasing and strictly concave in the spinoff's effort, f_i. The payoff of spinoff i becomes $p(f_i)e_i\pi_i(r_i) - C - f_i\kappa$ where κ is the cost of unit effort.

Moral Hazard without Adverse Selection: We find that the equilibrium outcome of the model with moral hazard but without adverse selection fails to explain the use of royalties along with equity stakes in a technology transfer agreement. In this model, we find that royalties cause effort distortion in addition to production distortion. On the other hand, equity only causes effort distortion. The negative effects of royalties outweigh that of equity and in the absence of asymmetric information on demand, we find that the TTO finds it optimal to use only equity. This result is consistent with Thursby et al. (2001), where equity was found to dominate royalty in a moral hazard framework (though in their model moral hazard was with respect to the production decision).

Moral Hazard and Adverse Selection: When the model of Section 4 is extended to include moral hazard the main findings remain unaltered. The TTO offers two contracts; one with equity only intended for the G-type and one with equity and royalties intended for the B-type. Furthermore, the equity stake offered to the B-type is higher than that offered to the G-type. This leads us to conclude that the presence of moral hazard does not invalidate our analysis and does not change the qualitative nature of our results.

6.2. Multiple spinoff types

We introduce multiple spinoff types by allowing 5 types which are equally likely, but with differing values of $0 < \theta_i < 1$. Spinoffs with higher θ_i can be thought of being of higher quality. The contracts offered by the TTO need to satisfy each type's individual rationality constraint. In addition, they need to satisfy all incentive compatibility constraints. There are now 4 incentive compatibility constraints for each of the 5 types. Overall, this setting gives rise to 25 constraints.

When we extend the original model to include 5 types we find that, provided equation (7) holds, the "best" type still receives a contract with only equity and no royalties. All other types receive a contract which includes both royalties and equity. Furthermore, as illustrated in figure 5, the equity stake (royalty rate) is increasing (decreasing) in θ_i, a measure of spinoff quality. Note that the monotonicity of contract terms is a standard result in information economics literature (Bolton and Dewatripont (2005), pages 77-81). This finding is consistent with our earlier results.

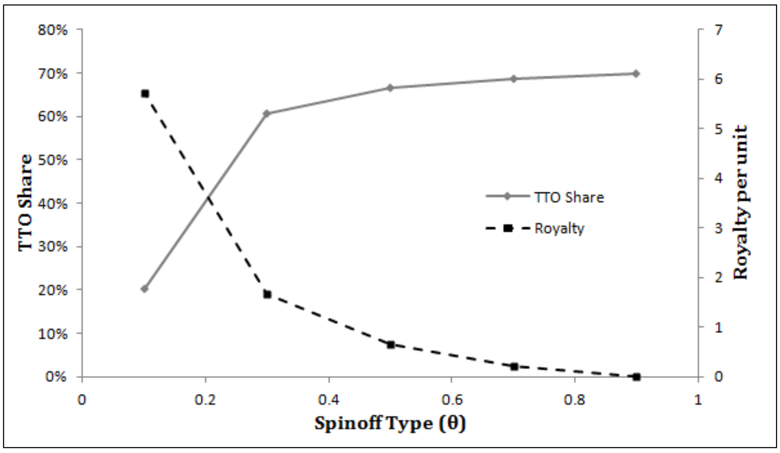


Figure 5 **Contracts Offered with Multiple Types**

7. Conclusion

In this paper we have looked at licensing contracts containing equity alongside royalties. We examine both fixed as well as variable royalties. In accordance with earlier work in the area we show that the inclusion of royalties causes production distortions. Nevertheless, we also find that, in the presence of asymmetric information on the market potential of the new product, equity only licenses fail to differentiate between more promising and less promising spinoffs, allowing the more promising spinoffs to accrue positive information rents. We find that this can be partially overcome by introducing royalties in contracts intended for less promising startups as the distortional effect of royalties allows them to act as a screening mechanism. Further, we find that a variable royalty scheme, as implemented by some university TTOs, is not only more effective as a screening mechanism (i.e. it allows screening without destroying as much value) but it is also applicable for any type of spinoff innovation.

Our models also helps to shed light on some empirical observations. Firstly, we provide a rational explanation for the apparently puzzling behavior of TTOs to insist on using royalties alongside equity in technology transfer despite their distortional effects; it is due to asymmetric information. Secondly, we explain why more experienced TTOs are more inclined toward equity deals; as universities gain more experience, they face less information asymmetry. Lastly, our work suggests three underlying causes for the empirically documented superior performance of equity over royalties. The first is selection bias; we find that royalties should be introduced only for projects that inherently have lower market potential. The second is that even for low value projects most of the value is still extracted through equity. And lastly, the nature of the value generated by royalties is twofold: The direct cash value it brings from the sales of the spinoff it applies to, and the indirect and arguably more important value it brings through allowing the TTO to retain more equity in spinoffs of higher value. Empirical investigations inevitably overlook the latter as it cannot be readily measured.

In addition to explaining existing empirical observations, our work generates hypotheses that can be tested with further empirical research. First, empirical work could try to verify whether the superior performance of equity as compared to royalty contracts is due to selection bias as our model suggests, or due to other reasons. Second, our model suggests that variable royalties are more effective than fixed royalties. Empirical work could study whether licenses with variable royalties do indeed lead to better outcomes for the TTO than licensing based on fixed royalties. Third, empirical work could also investigate our starting premise, that TTOs face an informational disadvantage vis-a-vis the spinoff management and whether this disadvantage dissipates with more experience in technology transfer. Existing survey studies of university technology transfer, such as AUTM's annual survey, collect data on how much licensing revenue is generated through cashed in equity versus other payment terms. Future surveys could include questions on perceived problems of asymmetric information.

Last but not least, we believe that recognizing and mitigating problems of asymmetric information in technology transfer can be an important driver in accelerating technology commercialization. While we must be cautious in applying theoretical results in practice, carefully designed contracts may enhance the ability of institutions that conduct basic research to retain more of the value they generate which, in turn, will ensure that they have the resources and incentives, both financial and organizational, to further fund research and better facilitate technology transfer. This will encourage spinoff creation with knock-on effects on the economic performance and job creation capacity of both local and national economies.

8. Appendix: Proofs of Propositions

Proof of proposition 2

Note that the feasible region is compact, since the equity stakes satisfy $0 \le e_i \le 1$ and the royalties are bounded below by zero and above by the participation constraints as $\pi_i(r)$ is continuous and decreasing in r. Since $\pi_i(r) = 0$ for $r \ge \max\{\frac{S_h}{k_h}, \frac{S_l}{k_l}\} - c$, we can conclude that the optimal royalties will have to satisfy $r_B, r_G \le \max\{\frac{S_h}{k_h}, \frac{S_l}{k_l}\} - c$. Since all payoffs are continuous, an appeal to the Weierstrass Theorem proves the existence of a maximum for this problem. The constraints $e_G \ge 0$ and $e_B \ge 0$ are redundant as they are implied by constraints (5) and (6). The payoff $U(e_G, e_B, r_G, r_B)$ is decreasing in both e_B and e_G. Therefore, at least one of the individual rationality constraints should be binding. If it were not, the TTO could decrease both e_B and e_G by the same fraction, which would leave the incentive compatibility constraints unaffected, but increase its payoff. We check two cases, in the first case IRB binds and in the second case IRG binds.

Case 1: IRB is binding which implies that $e_B = \frac{C}{\pi_B(r_B)}$. ICG becomes $e_G \pi_G(r_G) \ge e_B \pi_G(r_B) = \frac{C}{\pi_B(r_B)} \pi_G(r_B)$. Then, at least one of a) ICG or b) IRG need to be binding. This follows from the fact that, once we substitute the above expression for e_B into the relevant constraints, reducing e_G by some fraction does not affect ICB, and we can keep reducing e_G until at least one of IRG or ICG binds.

Case 1a: IRB and ICG are binding. The two binding constraints $e_B \pi_B(r_B) = C$ and $e_G \pi_G(r_G) = e_B \pi_G(r_B)$ allow us to eliminate e_B and e_G from the problem. Using this, IRG can now be written as $\pi_G(r_B) \ge \pi_B(r_B)$. The constraint $e_B \le 1$ can be written as $\pi_B(r_B) \ge C$ and the constraint $e_G \le 1$ can be written as $\pi_G(r_G) \ge C$. Next, we relax the problem by ignoring the ICB constraint, which holds at first best. We will check whether this constraint is satisfied at optimum. We will also ignore $e_G \le 1$ which will also check at the end. The relaxed program becomes

$$\max_{r_G, r_B \ge 0} U(r_G, r_B) = (1-\beta) U_G(r_G, r_B) + \beta U_B(r_B) \tag{14}$$

with $\pi_G(r_B) \ge \pi_B(r_B)$ and $\pi_B(r_B) \ge C$ which are equivalent to IRG and $e_B \le 1$ respectively. Note that r_G does not appear in the constraints except $r_G \ge 0$ and that

$$\frac{\partial U}{\partial r_G} = \begin{cases} -\frac{1}{2}(1-\beta)\left(\theta_G k_h + (1-\theta_G) k_l\right) r_G & \text{if } r_G < \min\{\frac{S_h}{k_h}, \frac{S_l}{k_l}\} - c \\ -\frac{1}{2}(1-\beta)\theta_G k_h r_G & \text{if } \frac{S_l}{k_l} - c \le r_G < \frac{S_h}{k_h} - c \\ -\frac{1}{2}(1-\beta)(1-\theta_G) k_l r_G & \text{if } \frac{S_h}{k_h} - c \le r_G < \frac{S_l}{k_l} - c \end{cases}$$

which is negative for all feasible $r_G > 0$ and zero for $r_G = 0$, therefore at the optimal contract $r_G = 0$. We are left with a single variable optimization problem. The first constraint implies $r_B \le \underline{r} = \frac{\frac{S_h}{\sqrt{k_h}} - \frac{S_l}{\sqrt{k_l}}}{\sqrt{k_h} - \sqrt{k_l}} - c$, and $\underline{r} > 0$ as a consequence of the assumption that a project of type h, in the absence or royalties, is more valuable than a project of type l ($V_h(0) > V_l(0)$). The second constraint implies $r_B \le \overline{r}$ where $\overline{r}$ is the solution of the equation $\pi_B(r) = C$. That $\overline{r} > 0$ exists and is unique is a consequence of the fact that $\pi_B(0) > C$, $\lim_{x \to \infty} \pi_B(x) = 0$ and $\pi_B(r)$ is continuous decreasing in r. The derivative of the objective function with respect to r_B is given by

$$\frac{\partial U}{\partial r_B} = \begin{cases} -\frac{\beta(\theta_B k_h + (1-\theta_B) k_l) r_B}{2} - \frac{(1-\beta)(\theta_G - \theta_B) C Q_l(r_B) Q_h(r_B)}{2\pi_B(r_B)^2} \left(\frac{S_h}{k_h} - \frac{S_l}{k_l}\right) & \text{if } r_B < \min\{\frac{S_h}{k_h}, \frac{S_l}{k_l}\} - c \\ -\frac{1}{2}\beta\theta_B k_h r_B & \text{if } \frac{S_l}{k_l} - c \le r_B < \frac{S_h}{k_h} - c \\ -\frac{1}{2}\beta(1-\theta_B) k_l r_B & \text{if } \frac{S_h}{k_h} - c \le r_B < \frac{S_l}{k_l} - c \end{cases}$$

When $\frac{S_h}{k_h} \geq \frac{S_l}{k_l}$ this derivative is always negative and the optimal solution is to set $r_B = 0$. In this case no separating contract exists. When $\frac{S_h}{k_h} < \frac{S_l}{k_l}$, then there exists a positive r^* in $(0, \frac{S_h}{k_h} - c)$ such that $\frac{\partial U}{\partial r_B}(r^*) = 0$. That such an r exists is a consequence of $\frac{\partial U}{\partial r_B}(0,0) > 0$, $\lim_{r \to \frac{S_h}{k_h} - c} \frac{\partial U}{\partial r_B}(0,r) < 0$ and $\frac{\partial U}{\partial r_B}(0,r)$ is continuous in $(0, \frac{S_h}{k_h} - c)$. Therefore the optimal royalty will be $\min\{r^*, \overline{r}, \underline{r}\}$.

We will now check if ICB and $e_G \leq 1$ are satisfied at optimum. At optimum, $r_G \leq r_B$. Since $\pi_i(r)$ is decreasing in r, $\frac{\pi_G(r_B)}{\pi_G(r_G)} \leq 1$ and since $e_G = e_B \frac{\pi_G(r_B)}{\pi_G(r_G)} \leq e_B \leq 1$. ICB can be written as $\pi_B(r_G)\pi_G(r_B) - \pi_B(r_B)\pi_G(r_G) \leq 0$. The LHS can be expressed as $\pi_B(r_G)\pi_G(r_B) - \pi_B(r_B)\pi_G(r_G) = \frac{\theta_G - \theta_B}{4}\left(\frac{S_h}{k_h} - \frac{S_l}{k_l}\right)(r_B - r_G)\left(Q_h(r_B)Q_l(r_G) + Q_h(r_G)Q_l(r_B)\right)$. The last bracket $(Q_h(r_B)Q_l(r_G) + Q_h(r_G)Q_l(r_B))$ is clearly positive. At the optimal contract $r_B \geq r_G = 0$ and $\frac{S_h}{k_h} - \frac{S_l}{k_l} < 0$ therefore ICB is satisfied.

Case 1b: Constraints IRB and IRG are binding. That IRG binds implies $e_G = \frac{C}{\pi_G(r_G)}$. Substituting the expressions for e_B and e_G into the ICG constraint and simplifying, we get $\pi_B(r_B) \geq \pi_G(r_B)$ which implies $V_l(r_B) \geq V_h(r_B)$. This last inequality cannot be satisfied if $\frac{S_h}{k_h} > \frac{S_l}{k_l}$. To see this, suppose $\frac{S_h}{k_h} > \frac{S_l}{k_l}$. If $r_B < \frac{S_l}{k_l} - c$ then $V_l(r_B) \geq V_h(r_B)$ implies that $r_B \geq \underline{r} = \frac{\frac{S_h}{\sqrt{k_h}} - \frac{S_l}{\sqrt{k_l}}}{\sqrt{k_h} - \sqrt{k_l}} - c$. Such an r_B exists only if $\underline{r} < \frac{S_l}{k_l} - c$ which implies that $\frac{S_h}{k_h} < \frac{S_l}{k_l}$ which is a contradiction. If $\frac{S_h}{k_h} - c > r_B \geq \frac{S_l}{k_l} - c$ then $V_l(r_B) = 0$ while $V_h(r_B) > 0$ and the inequality $V_l(r_B) \geq V_h(r_B)$ can never be satisfied. We restrict our attention to the case where $\frac{S_h}{k_h} \leq \frac{S_l}{k_l}$, in which case the constraint is satisfied by any royalty such that $r_B \geq \underline{r}$. Substituting the expressions for e_B and e_G into the ICB constraint, and simplifying, we get $\pi_G(r_G) \geq \pi_B(r_G)$ which implies $V_h(r_G) \geq V_l(r_G)$, which is satisfied for any r_G such that $\underline{r} \geq r_G \geq 0$. The optimization problem can be rewritten as

$$\max_{r_G, r_B} U(r_G, r_B) = (1-\beta)U_G(e_G(r_G), r_G) + \beta U_B(e_B(r_B, r_G), r_B), \tag{15}$$

such that $r_G \geq 0$, $r_B \geq \underline{r}$, $e_G(r_B) = \frac{C}{\pi_B(r_B)}$ $e_G(r_G) = \frac{C}{\pi_G(r_G)}$ which are equivalent to ICB, ICG, IRB and IRG respectively and $r_B \leq \overline{r}$ which is equivalent to $e_B \leq 1$, as well as $\frac{S_h}{k_h} \leq \frac{S_l}{k_l}$. The derivatives of the objective function with respect to the decision variables are given by

$$\frac{\partial U}{\partial r_G} = \begin{cases} -\frac{1}{2}(1-\beta)\left(\theta_G k_h + (1-\theta_G)k_l\right) r_G & \text{if } r_G < \frac{S_h}{k_h} - c \\ -\frac{1}{2}(1-\beta)(1-\theta_G)k_h r_G & \text{if } \frac{S_h}{k_h} - c \leq r_G < \frac{S_l}{k_l} - c \end{cases}$$

$$\frac{\partial U}{\partial r_B} = \begin{cases} -\beta\frac{1}{2}(\theta_B k_h + (1-\theta_B)k_l) r_B & \text{if } r_B < \frac{S_h}{k_h} - c \\ -\beta\frac{1}{2}(1-\theta_B)k_l r_B & \text{if } \frac{S_h}{k_h} - c \leq r_B < \frac{S_l}{k_l} - c \end{cases}$$

Since both derivatives are negative, the maximum of the program is achieved at $r_G = 0$, $r_B = \underline{r}$, $e_G = \frac{C}{\pi_G(0)}$ and $e_B = \frac{C}{\pi_B(\underline{r})}$ whenever $\underline{r} \leq \overline{r}$. Otherwise, $r_B \leq \overline{r}$ is violated and no solution exists. This solution is a special case of that found in case 1a.

Case 2: IRG is binding. This implies that $e_G = \frac{C}{\pi_G(r_G)}$. As with case 1, at least one of the following two constraints need to be binding: a) ICB or b) IRB.

Case 2a: IRG and ICB are binding which implies $e_B = \frac{C}{\pi_B(r_B)} \frac{\pi_B(r_G)}{\pi_G(r_G)}$. IRB becomes $\pi_B(r_G) \geq \pi_G(r_G)$ which further implies $V_l(r_G) \geq V_h(r_G)$. As in case 1b, this last constraint can never be satisfied if $\frac{S_h}{k_h} > \frac{S_l}{k_l}$. We restrict our attention to the case where $\frac{S_h}{k_h} \leq \frac{S_l}{k_l}$, in which case the constraint is satisfied by any royalty such that $r_G \geq \underline{r}$. Furthermore, ICG becomes $\pi_G(r_G)\pi_B(r_B) - \pi_B(r_G)\pi_G(r_B) \geq 0$ which can be further simplified to $V_l(r_G)V_h(r_B) - V_l(r_B)V_h(r_G) \leq 0$. Since $V_l(r_G) \geq V_h(r_G)$ a sufficient (but not necessary) condition for the inequality above to hold is $V_h(r_B) - V_l(r_B) < 0$ or $r_B > \underline{r}$. Therefore the maximum of the program of equation (2) under the assumption that the individual rationality constraint of the G type holds will be no better than the maximum of the relaxed program below

$$\max_{r_G, r_B} U(r_G, r_B) = (1-\beta)U_G(e_G(r_G), r_G) + \beta U_B(e_B(r_B, r_G), r_B) \tag{16}$$

with $r_G \geq \underline{r}$ and $r_B \geq \underline{r}$ which are equivalent to IRB and the relaxed version of ICG respectively, and $e_G(r_G) = \frac{C}{\pi_G(r_G)}$, $e_B(r_G, r_B) = e_G(r_G)\frac{\pi_B(r_G)}{\pi_B(r_B)}$ and $\frac{S_h}{k_h} \leq \frac{S_l}{k_l}$. The derivatives of the objective function with respect to the decision variables are given by

$$\frac{\partial U}{\partial r_B} = \begin{cases} -\frac{1}{2}\beta\left(\theta_B k_h + (1-\theta_B)k_l\right) r_B & \text{if } r_B < \frac{S_h}{k_h} - c \\ -\frac{1}{2}\beta(1-\theta_B)k_l r_B & \text{if } \frac{S_h}{k_h} - c \leq r_B < \frac{S_l}{k_l} - c \end{cases}$$

$$\frac{\partial U}{\partial r_G} = \begin{cases} -\beta e_G(\theta_G - \theta_B)\frac{Q_l(r_G)Q_h(r_G)}{\pi_G(r_G)}\left(\frac{Q_l(r_G)}{k_l} - \frac{Q_h(r_G)}{k_h}\right) - \frac{(1-\beta)}{2}\left(\theta_G k_h + (1-\theta_G)k_l\right) r_G & \text{if } r_G < \frac{S_h}{k_h} - c \\ -\frac{1}{2}(1-\beta)(1-\theta_G)k_l r_G & \text{if } \frac{S_h}{k_h} - c \leq r_G < \frac{S_l}{k_l} - c \end{cases}$$

The derivative wrt r_B is clearly negative, while the derivative wrt r_G is negative since $Q_h(r_G) \leq Q_l(r_G)$ for $r_G \geq \underline{r}$ and $k_h > k_l$. As both derivatives are negative in the feasible region, the maximum of the program (16) is achieved when $r_G = r_B = \underline{r}$ and $e_G = e_B = \frac{C}{\pi_G(\underline{r})}$. However, this is not a separating equilibrium as both types are offered the same contract. But as shown in Section 4.1.1, from the class of pooling equilibria the optimal one has zero royalties and $e_G = e_B = \frac{C}{\pi_B(0)}$. Therefore, the TTO cannot do any better than the equity only pooling equilibrium by trying to charge high enough royalties to the G type in order to make its participation constraint binding.

Case 2b: Constraints IRG and IRB bind. This case is equivalent to case 1b. This completes the proof. □

Proof of proposition 3

Note that the feasible region is compact, as the equity stakes satisfy $0 \leq e_i \leq 1$ and the royalties are bounded below by zero and above by the participation constraints (as $\pi_i(r_{il}, r_{ih})$ is continuous and decreasing in r_{il} and r_{ih}). Since all payoffs are continuous, an appeal to the Weierstrass Theorem proves the existence of a maximum for this problem. The constraints $e_G, e_B \geq 0$ are redundant as they are implied by the individual rationality constraints of equations (12) and (13). Since the TTO's payoff is decreasing in both e_B and e_G at least one of the participation constraints will be binding. If it was not, the TTO could reduce both e_G and e_B by the same fraction without affecting any of the incentive compatibility constraints and increase its profits. We check two cases. In the first case IRB binds while in the second case IRG binds.

Case 1: IRB is binding ($e_B\pi_B(r_{Bl}, r_{Gh}) = C$). Using this, ICG can be written as $e_G\pi_G(r_{Gl}, r_{Gh}) \geq e_B\pi_G(r_{Bl}, r_{Bh}) = \frac{C}{\pi_B(r_{Bl}, r_{Bh})}\pi_G(r_{Bl}, r_{Bh})$. Then, at least one of a) ICG or b) IRG also need to be binding. Otherwise, one could decrease e_G, without affecting ICB until one of ICG or IRG bind while increasing the objective value.

Case 1a: IRB and ICG bind. These two binding constraints ($e_B\pi_B(r_{Bl}, r_{Bh}) = C$ and $e_G\pi_G(r_{Gl}, r_{Gh}) = e_B\pi_G(r_{Bl}, r_{Bh})$) eliminate e_B and e_G from the problem. Using this, IRG can now be written as $\pi_G(r_{Bl}, r_{Bh}) \geq \pi_B(r_{Bl}, r_{Bh})$. The constraint $e_B \leq 1$ can be written as $\pi_B(r_{Bl}, r_{Bh}) \geq C$ and the constraint $e_G \leq 1$ can be written as $\pi_G(r_{Gl}, r_{Gh}) \geq C$. Next, we relax the problem by ignoring ICB and $e_G \leq 1$. We will check whether these constraints are satisfied at optimum. The relaxed program becomes

$$\max_{r_{Gl}, r_{Gh}, r_{Bl}, r_{Bh} \geq 0} U(r_{Gl}, r_{Gh}, r_{Bl}, r_{Bh}) = (1-\beta)U_G(e_G(r_{Gl}, r_{Gh}, r_{Bl}, r_{Bh}), r_{Gl}, r_{Gh}) + \beta U_B(e_B(r_{Bl}, r_{Bh}), r_{Bl}, r_{Bh}),$$

such that $\pi_G(r_{Bl}, r_{Bh}) - \pi_B(r_{Bl}, r_{Bh}) \geq 0$ (equivalent to IRG), $\pi_B(r_{Bl}, r_{Bh}) - C \geq 0$ (equivalent to $e_B \leq 1$), with $e_B(r_{Bl}, r_{Bh}) = \frac{C}{\pi_B(r_{Bl}, r_{Gh})}$, $e_G(r_{Gl}, r_{Gh}, r_{Bl}, r_{Bh}) = e_B(r_{Bl}, r_{Bh})\frac{\pi_G(r_{Bl}, r_{Bh})}{\pi_G(r_{Gl}, r_{Gh})}$. Note that r_{Gl} and r_{Gh} do not appear in the constraints except $r_{Gh}, r_{Gl} \geq 0$ and that $\frac{\partial U}{\partial r_{Gl}} = -\frac{1}{2}(1-\beta)(1-\theta_G)k_l r_{Gl}$, $\frac{\partial U}{\partial r_{Gh}} = -\frac{1}{2}(1-\beta)\theta_G k_h r_{Gh}$. Therefore the optimal contract will have $r_{Gl} = r_{Gh} = 0$. Using this we can further simplify the optimization problem to

$$\max_{r_{Bl}, r_{Bh}} U(r_{Bl}, r_{Bh}) = (1-\beta)U_G(r_{Bl}, r_{Bh}) + \beta U_B(r_{Bl}, r_{Bh})$$

such that $h_1 = \pi_G(r_{Bl}, r_{Bh}) - \pi_B(r_{Bl}, r_{Bh}) \geq 0$ (equivalent to IRG), $h_2 = \pi_B(r_{Bl}, r_{Bh}) - C \geq 0$ (equivalent to $e_B \leq 1$), $h_3 = r_{Bh} \geq 0$, $h_4 = r_{Bl} \geq 0$.

This problem has four inequality constraints. To check if the constraint qualification holds, we first identify all constraints that could in principle hold at the optimum. Note that since we have two decision variables, at most two constraints can be binding. Therefore, there are 10 combinations of constraints that can be binding: $h_E \in \{\emptyset, h_1, h_2, h_3, h_4, (h_1, h_2), (h_1, h_3), (h_1, h_4), (h_2, h_3), (h_2, h_4), (h_3, h_4)\}$. We find that the constraint qualification holds for any positive production. The Lagrangian of the problem is given by

$$L(r_{Bl}, r_{Bh}) = U(r_{Bl}, r_{Bh}) + \lambda_1 h_1 + \lambda_2 h_2 + \lambda_3 h_3 + \lambda_4 h_4$$

and the critical points will satisfy the following system of equations

1. $\frac{\partial U}{\partial r_{Bh}} - \lambda_1(\theta_G - \theta_B)Q_h(r_{Bh}) - \lambda_2\theta_G Q_h(r_{Bh}) + \lambda_3 = 0,$
2. $\frac{\partial U}{\partial r_{Bl}} + \lambda_1(\theta_G - \theta_B)Q_h(r_{Bh}) - \lambda_2\theta_B Q_l(r_{Bl}) + \lambda_4 = 0,$
3. $\lambda_1 \geq 0,\ \pi_G(r_{Bl}, r_{Bh}) - \pi_B(r_{Bl}, r_{Bh}) \geq 0,\ \lambda_1(\pi_G(r_{Bl}, r_{Bh}) - \pi_B(r_{Bl}, r_{Bh})) = 0,$
4. $\lambda_2 \geq 0,\ \pi_B(r_{Bl}, r_{Bh}) - C \geq 0,\ \lambda_2(\pi_B(r_{Bl}, r_{Bh}) - C) = 0,$
5. $\lambda_3 \geq 0,\ r_{Bh} \geq 0,\ \lambda_3 r_{Bh} = 0,$
6. $\lambda_4 \geq 0,\ r_{Bl} \geq 0,\ \lambda_4 r_{Bl} = 0.$

Where the derivatives of the objective function wrt the royalties r_{Bh} and r_{Bl} are given by the expressions:

$$\frac{\partial U}{\partial r_{Bh}} = -\frac{1}{2}\beta\theta_B k_h r_{Bh} + (1-\beta)e_B(r_{Bl}, r_{Bh})Q_h(r_{Bh})(\theta_G - \theta_B)\frac{V_l(r_{Bl})}{\pi_B(r_{Bl}, r_{Bh})},$$
$$\frac{\partial U}{\partial r_{Bl}} = -\frac{1}{2}\beta(1-\theta_B)k_l r_{Bl} - (1-\beta)e_B(r_{Bl}, r_{Bh})Q_l(r_{Bl})(\theta_G - \theta_B)\frac{V_h(r_{Bh})}{\pi_B(r_{Bl}, r_{Bh})}.$$

We will look for critical points for all combinations of binding constraints as identified before.

1. Binding constraints $C = \{\emptyset\}$. This implies that $r_{Bh} > 0$ and $r_{Bl} > 0$ and by complementary slackness $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = 0$. Since $\frac{\partial U}{\partial r_{Bl}} < 0$ we conclude that there cannot exist a positive r_{Bl} that can satisfy equation 2.

2. Binding constraints $C = \{h_1\}$. This case implies that $r_{Bh} > 0$, $r_{Bl} > 0$ and $\lambda_1 > 0$ and by complementary slackness $h_1 = \lambda_2 = \lambda_3 = \lambda_4 = 0$. From $h_1 = 0$ we have $\pi_G(r_{Bl}, r_{Bh}) = \pi_B(r_{Bl}, r_{Bh})$ which implies $V_h(r_{Bh}) = V_l(r_{Bl})$. From equation 1 we have $-\frac{1}{2}\beta\theta_B k_h r_{Bh} + (1-\beta)(\frac{C}{V_h(r_{Bh})} - \lambda_1)(\theta_G - \theta_B)Q_h(r_{Bh}) = 0$ which we can solve for λ_1 and substitute to equation 2 to get $(1-\theta_B)k_l r_{Bl} + \theta_B r_{Bh}\sqrt{k_h k_l} = 0$. Clearly there cannot exist positive r_{Bl} and r_{Bh} that can satisfy this equation.

3. Binding constraints $C = \{h_2\}$. This case implies that $r_{Bh} > 0$, $r_{Bl} > 0$ and $\lambda_2 > 0$ and by complementary slackness $h_2 = \lambda_1 = \lambda_3 = \lambda_4 = 0$. From equation 2, since $\frac{\partial U}{\partial r_{Bl}} < 0$ we can conclude that there cannot exist a positive r_{Bl} than can satisfy this equation.

4. Binding constraints $C = \{h_3\}$. This case implies that $r_{Bl} > 0$ and $\lambda_3 > 0$ and by complementary slackness $r_{Bh} = \lambda_1 = \lambda_2 = \lambda_4 = 0$. From equation 2, since $\frac{\partial U}{\partial r_{Bl}} < 0$ we can conclude that there cannot exist a positive r_{Bl} than can satisfy this equation.

5. Binding constraints $C = \{h_4\}$. This case implies that $r_{Bh} > 0$ and $\lambda_4 > 0$ and by complementary slackness $r_{Bl} = \lambda_1 = \lambda_2 = \lambda_4 = 0$. From equation 1, r_{Bh} is given by $\frac{\partial U(0, r_{Bh})}{\partial r_{Bh}} = 0$ and this solution does not violate the other constraints as long as $\pi_G(0, r_{Bh}) > \pi_B(0, r_{Bh})$ and $\pi_B(0, r_{Bh}) > C$. Since, $\frac{\partial^2 U(0, r_{Bh})}{\partial r_{Bh}^2} = -\frac{1}{2}\beta\theta_B k_h - \frac{1}{2}\frac{(1-\beta)(\theta_G - \theta_B)(1-\theta_B)(V_l(r_{Bh}))^2 C k_h}{(\pi_B(r_{Bh}))^3} < 0$, $\arg\max\{U(0, r_{Bh}) | r_{Bh} \in D\}$ is either empty or contains one point (where $D = \{r_{Bh} | h_i(r_{Bh}) \geq 0, i = 1..3\}$). Such an r exists, i.e. D is non-empty, because $\frac{\partial U(0,0)}{\partial r_{Bh}} > 0$, $\lim_{r \to \frac{S_h}{k_h} - c} \frac{\partial U(0,r)}{\partial r_{Bh}} < 0$ and $\frac{\partial U(0,r)}{\partial r_{Bh}}$ is continuous in $(0, \frac{S_h}{k_h} - c)$. Hence, r^* is unique.

6. Binding constraints $C = \{h_1, h_2\}$. This case implies that $r_{Bh} > 0$, $r_{Bl} > 0$, $\lambda_1 > 0$ and $\lambda_2 > 0$ and by complementary slackness $h_1 = h_2 = \lambda_3 = \lambda_4 = 0$. As we have shown in case 2, when $h_1 = 0$ there cannot exist a positive r_{Bl} that can satisfy equation 2.

7. Binding constraints $C = \{h_1, h_3\}$. This case implies that $r_{Bl} > 0$, $\lambda_1 > 0$ and $\lambda_3 > 0$ and by complementary slackness $r_{Bh} = h_1 = \lambda_2 = \lambda_4 = 0$. As we have shown in case 2, when $h_1 = 0$ there cannot exist a positive r_{Bl} that can satisfy equation 2.

8. Binding constraints $C = \{h_1, h_4\}$. This case implies that $r_{Bh} > 0$, $\lambda_1 > 0$ and $\lambda_4 > 0$ and by complementary slackness $r_{Bl} = h_1 = \lambda_2 = \lambda_3 = 0$. From $h_1 = 0$ we have $\pi_G(0, r_{Bh}) = \pi_B(0, r_{Bh})$ which implies $r_{Bh} = \underline{r} = \frac{S_h - ck_h}{k_h} - (S_l - c)\sqrt{\frac{1}{k_h k_l}}$.

9. Binding constraints $C = \{h_2, h_3\}$. This case implies that $r_{Bl} > 0$, $\lambda_2 > 0$ and $\lambda_3 > 0$ and by complementary slackness $r_{Bh} = h_2 = \lambda_1 = \lambda_4 = 0$. From equation 2, since $\frac{\partial U}{\partial r_{Bl}} < 0$ we can conclude that there cannot exist a positive r_{Bl} than can satisfy this equation.

10. Binding constraints $C = \{h_2, h_4\}$. This case implies that $r_{Bh} > 0$, $\lambda_2 > 0$ and $\lambda_4 > 0$ and by complementary slackness $r_{Bl} = h_2 = \lambda_1 = \lambda_3 = 0$. The constraint $h_2 = 0$ implies $r_{Bh} = \overline{r} = \frac{S_h - ck_h}{k_h} - \sqrt{\left[C - (1-\theta_B)\frac{(S_l - ck_l)^2}{4k_l}\right]\frac{4}{k_h \theta_B}}$.

To summarize, the solution has $r_{Bl} = 0$ and $r_{Bh} = \min\{\underline{r}, r^*, \overline{r}\}$. We are left to check that $e_G \le 1$ and that ICB, $(\pi_B(r_{Bl}, r_{Bh})\pi_G(r_{Gl}, r_{Gh}) \ge \pi_G(r_{Bl}, r_{Bh})\pi_B(r_{Gl}, r_{Gh}))$, hold at optimum. Starting from e_G we have $e_G = e_B \frac{\pi_G(0, r_{Bh})}{\pi_G(0,0)} < e_B \le 1$, where the first inequality follows from the fact that $\pi_G(0, r)$ is decreasing in r. The ICB constraint at the optimum is $\pi_B(0, r_{Bh})\pi_G(0,0) - \pi_G(0, r_{Bh})\pi_B(0,0) = (\theta_G - \theta_B)V_l(0)(V_h(0) - V_h(r_{Bh}) \ge 0$, where the last inequality follows from the facts that $\theta_G > \theta_B$, $r_{Bh} \ge 0$ and $V_l(r)$ is decreasing in r.

Case 1b: IRB and IRG bind. These two binding constraints ($e_B \pi_B(r_{Bl}, r_{Bh}) = C$ and $e_G \pi_G(r_{Gl}, r_{Gh}) = C$), eliminate e_B and e_G from the problem. Using this, ICG can be written as $\pi_B(r_{Bl}, r_{Bh}) \ge \pi_G(r_{Bl}, r_{Bh})$ or equivalently as $V_l(r_{Bl}) \ge V_h(r_{Bh})$. Similarly, ICB can be rewritten as $V_h(r_{Gh}) \ge V_l(r_{Bl})$. The constraint $e_i \le 1$ can be written as $\pi_i(r_{il}, r_{ih}) \ge C$. We relax the problem by ignoring ICB and $e_G \le 1$ which we will check at the end. The relaxed program becomes

$$\begin{aligned}\max_{r_{Gl}, r_{Gh}, r_{Bl}, r_{Bh} \ge 0} U(r_{Gl}, r_{Gh}, r_{Bl}, r_{Bh}) &= (1-\beta)U_G(e_G(r_{Gl}, r_{Gh}), r_{Gl}, r_{Gh}) \\ &+ \beta U_B(e_B(r_{Bl}, r_{Bh}), r_{Bl}, r_{Bh})\end{aligned}$$

such that $V_l(r_{Bl}) \ge V_h(r_{Bh})$ (equivalent to ICG), $\pi_B(r_{Bl}, r_{Bh}) \ge C$ (equivalent to $e_B \le 1$) with $e_B(r_{Bl}, r_{Bh}) = \frac{C}{\pi_B(r_{Bl}, r_{Gh})}$, $e_G(r_{Gl}, r_{Gh}) = \frac{C}{\pi_G(r_{Gl}, r_{Gh})}$. Note that r_{Gl} and r_{Gh} do not appear in the constraints except $r_{Gh}, r_{Gl} \ge 0$ and that $\frac{\partial U}{\partial r_{Gl}} = -\frac{1}{2}(1-\beta)(1-\theta_G)k_l r_{Gl}$, $\frac{\partial U}{\partial r_{Gh}} = -\frac{1}{2}(1-\beta)\theta_G k_h r_{Gh}$.

Therefore the optimal contract will have $r_{Gl} = r_{Gh} = 0$. Using this we can further simplify the optimization problem to

$$\max_{r_{Bl}, r_{Bh} \geq 0} U(r_{Bl}, r_{Bh}) = (1-\beta)U_G(r_{Bl}, r_{Bh}) + \beta U_B(r_{Bl}, r_{Bh})$$

such that $V_l(r_{Bl}) \geq V_h(r_{Bh})$ (equivalent to ICG), $\pi_B(r_{Bl}, r_{Bh}) - C \geq 0$ (equivalent to $e_B \leq 1$). Note that reducing r_{Bl} or r_{Bh} does not affect $(e_B \leq 1)$ when it is already satisfied. Further note that $\frac{\partial U}{\partial r_{Bl}} = -\frac{1}{2}\beta(1-\theta_B)k_l r_{Bl}$, $\frac{\partial U}{\partial r_{Bh}} = -\frac{1}{2}\beta\theta_B k_h r_{Bh}$. When $r_{Bl} = 0$ then ICG implies $r_{Bh} \geq \underline{r}$ and when $r_{Bl} > 0$ the constraint $V_l(r_{Bl}) \geq V_h(r_{Bh})$ implies $r_{Bh} > \underline{r}$. Since the objective function U is decreasing in both r_{Bl} and r_{Bh}, it is optimal to set $r_{Bl} = 0$ and ICG is equivalent to $r_{Bh} \geq \underline{r}$. When $r_{Bl} = 0$,$(e_B \leq 1)$ can be expressed as $r_{Bh} \leq \overline{r}$. The optimization problem can now be written as

$$\max_{r_{Bl}, r_{Bh}} U(r_{Bl}, r_{Bh}) = (1-\beta)U_G(r_{Bl}, r_{Bh}) + \beta U_B(r_{Bl}, r_{Bh})$$

such that $r_{Bl} = 0,\ r_{Bh} \geq \underline{r},\ r_{Bh} \leq \overline{r}$ Since U is decreasing in r_{Bh} it is optimal to set $r_{Bh} = \underline{r}$ whenever $\underline{r} \leq \overline{r}$, otherwise no solution exists. The two ignored constrains are satisfied; ICB because $V_h(0) \geq V_l(0)$, and $e_G \leq 1$ because $\pi_G(0,0) > \pi_B(r_{Bl}, r_{Bh}) \geq C$. Note that this solution is a special case of that found in case 1a.

Case 2: IRG is binding ($e_G \pi_G(r_{Gl}, r_{Gh}) = C$). In a similar fashion to Case 1, at least one of a) ICB or b) IRB also need to be binding.

Case 2a: IRG and ICB bind. ICB can be written as $e_B \pi_B(r_{Bl}, r_{Bh}) = \frac{C}{\pi_G(r_{Gl}, r_{Gh})}\pi_B(r_{Gl}, r_{Gh})$, while IRB can be written as $\pi_B(r_{Gl}, r_{Gh}) \geq \pi_G(r_{Gl}, r_{Gh})$. The last inequality is equivalent to $V_l(r_{Gl}) \geq V_h(r_{Gh})$. A sufficient but not necessary condition for this to hold is $r_{Gh} \geq r_{Gl}$. ICG becomes $\pi_G(r_{Gl}, r_{Gh})\pi_B(r_{Bl}, r_{Bh}) \geq \pi_B(r_{Gl}, r_{Gh})\pi_G(r_{Bl}, r_{Bh})$ which is equivalent to $V_l(r_{Gl})V_h(r_{Bh}) - V_h(r_{Gh})V_l(r_{Bl}) \leq 0$. Since $V_l(r_{Gl}) \geq V_h(r_{Gh})$, a sufficient condition for the inequality $V_l(r_{Gl})V_h(r_{Bh}) - V_h(r_{Gh})V_l(r_{Bl}) \leq 0$ to hold is $V_l(r_{Bl}) \geq V_h(r_{Bh})$ which implies $r_{Bh} \geq r_{Bl}$. Therefore the maximum of the original problem will be no greater than the maximum of the program below.

$$\begin{aligned}\max_{r_{Gl}, r_{Gh}, r_{Bl}, r_{Bh} \geq 0} U(r_{Gl}, r_{Gh}, r_{Bl}, r_{Bh}) &= (1-\beta)U_G(e_G(r_{Gl}, r_{Gh}), r_{Gl}, r_{Gh}) \\ &+ \beta U_B(e_B(r_{Gl}, r_{Gh}, r_{Bl}, r_{Bh}), r_{Bl}, r_{Bh})\end{aligned}$$

such that $r_{Bh} \geq r_{Bl}$ (relaxed version of ICG), $r_{Gh} \geq r_{Gl}$ (relaxed version of IRB), $\pi_B(r_{Bl}, r_{Bh}) \geq C$ (equivalent to $e_B \leq 1$), $\pi_G(r_{Gl}, r_{Gh}) \geq C$ (equivalent to $e_G \leq 1$) with $e_G(r_{Gl}, r_{Gh}) = \frac{C}{\pi_G(r_{Gl}, r_{Gh})}$, $e_B(r_{Bl}, r_{Bh}) = e_G \frac{\pi_B(r_{Gl}, r_{Gh})}{\pi_B(r_{Bl}, r_{Bh})}$. The derivatives of the objective function U with respect to r_{Bh} and r_{Gh} are given by

$$\frac{\partial U}{\partial r_{Bh}} = -\frac{1}{2}\beta\theta_B k_h r_{Bh},\ \frac{\partial U}{\partial r_{Gh}} = \beta e_G Q_h(r_{Gh})\left(\theta_B - \theta_G \frac{\pi_B(r_{Gl}, r_{Gh})}{\pi_G(r_{Gl}, r_{Gh})}\right) - \frac{1}{2}(1-\beta)(\theta_G k_h r_{Gh}),$$

which are both negative ($\frac{\partial U}{\partial r_{Gh}}$ is negative because $\theta_G > \theta_B$ and $\frac{\pi_B(r_{Gl}, r_{Gh})}{\pi_G(r_{Gl}, r_{Gh})} \geq 1$ due to IRB). Reducing r_{Gh} or r_{Bh} does not affect the constraints $e_B \leq 1$ and $e_G \leq 1$. This suggests that it is optimal to set $r_{Gh} = r_{Gl}$ and $r_{Bh} = r_{Bl}$ which makes the problem equivalent to the fixed royalty contract of Case 2a of proposition 2 where we had shown that an equity only pooling contract dominates an equity fixed royalty contract.

Case 2b: IRG and IRB are binding. This case is equivalent to case 1b. This completes the proof. □

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