University Inventions Licensed Through Start-Ups

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Much of the theoretical and empirical work in the licensing of university inventions has focused on an established firm as the licensee. However, another option is licensing to a start-up firm in which the faculty inventor shares ownership with a venture capitalist. In this paper, we show conditions under which start-ups will be used instead of established firms. In a multi-stage game, effort by both the inventor and licensee to bring an innovation to successful commercialization is greater when the inventor has an ownership stake in a start-up firm. If inventor effort is very important relative to firm effort in bringing a product to successful commercialization, then technology transfer offices are more likely to license to a start-up firm at a lower royalty rate and fixed fee. In general, we show that start-ups are more likely to be used as the importance of inventor effort increases relative to firm effort, and as search costs of finding venture capital financing decrease.

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1 Introduction

The Bayh-Dole Act of 1980 led to an explosion in the growth of technology transfer offices in U.S. universities, as well as a substantial increase in the commercialization of university inventions and resulting revenue. Gross license royalties paid to universities in the Association of University Technology Managers (AUTM) annual surveys for 1993 through 2002 increased by a remarkable 284%, from roughly $238 million to $915 million. The commercialization of university inventions was dominated by established firms during this period. On average, each surveyed university annually licensed 25 inventions to established firms, but only 3 inventions to start-up firms. This ratio has been reasonably constant during this period as well. AUTM data show that the number of licenses executed with established firms grew by 90% during this time period, while the number of licenses with start-ups grew by 105%. The 2008 survey indicates that about 12% of all licenses and options executed were to new firms. There seems to be a lack of systematic theory that would suggest why some universities such as MIT. generate many new firms licensing university inventions, while others such as Duke and Columbia, don't (see Di Gregorio and Shane 2003). Also, given the embryonic nature of most university inventions, it is somewhat surprising that there has not been more commercialization via start-ups.

In this paper, we formalize the behavior of the technology transfer office (TTO), the faculty inventor, and the licensees (established firm or start-up firm) in a game-theoretic model that reveals some factors that make the commercialization of university inventions more likely to occur through start-up firms than established firms. Licensing to a start-up has the benefit to the TTO of allowing the inventor to have partial ownership, which may induce more effort from both the inventor and venture capitalist relative to an established firm license. Specifically, we show that when the effect of inventor effort on the probability of success is relatively stronger than that of the venture capitalist (VC) or established firm, then two important incentive effects exist. First, royalty rates are inversely related to the incentives of both the inventor and either licensee (VC or established firm) to expend effort to develop the invention. Thus, a higher (lower) royalty rate results in lower (greater) equilibrium effort by both the inventor and the licensee. Second, the inventor's ownership share in a startup is directly related to the incentives of both the inventor and either licensee to expend effort to develop the invention. Thus, a higher (lower) royalty rate results in greater (lower) equilibrium effort by both the inventor and the licensee. Given these incentive effects, under reasonable conditions, a higher royalty rate chosen by the TTO results in both a lower inventor ownership share in a start-up and a lower level of inventor effort. Therefore, if the search costs of finding a VC to be a licensee are low relative to those of finding an established firm, then licensing to a start-up and using a lower royalty rate (relative to an established firm licensee) becomes a more attractive option because of the effects of increased effort on the TTO's expected returns. The contribution of this paper is to reveal the important interaction of royalty rates, ownership, and effort in the transfer of technology, and to better equip TTOs in making optimal licensing decisions on behalf of the universities they represent.

In the next section we provide a brief review of the relevant literature. In section 3 we develop and analyze the model, a three-stage game between the TTO, inventor, and licensee. In the first stage, given an invention disclosure, the TTO determines whether to try to sell a license to an established firm, or to allow the inventor to seek a venture capitalist (or angel investor) to help form a start-up which licenses the invention. In addition, the TTO also chooses the terms of the licensing contract, a royalty and a fixed fee. In the second stage, if the TTO has decided not to seek an established firm as a licensee, then the inventor negotiates its ownership share with the venture capitalist. In the third stage, the inventor and licensee levels of effort to increase the invention's probability of successful commercialization. If the invention is a success, the firm produces and pays royalties to the TTO (since they still hold the patent in either case). If the invention fails, the game ends.

Working backwards, in the final stage we provide conditions under which an equilibrium for the development game exists, and characterize it by showing how the equilibrium efforts vary with the royalty rate, the fixed fee, the ownership share, and the commercialization cost. For the second stage, we show conditions on the effort cost functions, the ownership share, and the commercialization cost under which a contract with a startup is more likely to be executed. We also show conditions under which the equilibrium ownership share is decreasing in the royalty rate. Finally, we analyze the TTO's problem and derive conditions under which licensing to a startup is more likely.

We conclude in the final section.

2 Literature Review

The results contribute to the growing literature on the licensing of university inventions, which has predominantly focused on the effects of the Bayh-Dole Act, and the behavior of inventors and TTOs. Jensen and Thursby (2001), in their seminal paper, show that inventor effort is critical to success of the innovation. As such, it is important for inventor income to be tied in some way to licensee's output through royalties or equity (the latter being more efficient). Lach and Schankerman (2008) also reveal a link between inventor cash flow rights and licensing outcomes. Greater royalty shares to the inventor are correlated with higher average value and income of innovations. Similarly, we show that both royalties and equity stakes for the faculty inventor have strong incentive effects on effort and license revenue.

Other papers focus on the function of TTOs and other intermediaries in technology transfer. Jensen *et al.* (2003) use survey data to reveal that TTOs have a dual function in maximizing returns for the faculty inventor and the university, which alters the timing of disclosure by the faculty inventor. Hoppe and Ozdenoren (2005) examine the beneficial function of intermediaries to sort profitable from unprofitable innovations. Macho-Stadler *et al.* (2007) show that when asymmetric information exists, TTOs may signal higher quality innovations through its decision to shelve projects. A large TTO that shelves inventions under certain circumstances can increase the expected value of the invention, which may reduce agreements but increase average returns. Macho-Stadler *et al.* (2008) study the optimal allocation of capital costs and founders shares among the TTO, inventor, and venture capitalist for a university start-up. They show that when the moral hazard problem is acute, the inventor not only must be given founder shares, but also may be required to provide financial capital, in order to guarantee she provides effort in the venture. Thursby *et al.* (2009) show that license contracts can incorporate milestone payments and annual payments to decrease moral hazard and adverse selection problems.

The distinguishing feature of the theoretical model in our paper is that, unlike much of the existing literature that uses a generic licensee, the choice between targeting an established firm versus a start-up (through venture capital financing) as a licensee is not trivial. In that vein, our work is most closely tied to Chukumba and Jensen (2005), who first modeled the choice between licensing to an established firm versus a start-up, finding that the choice depends on the relative costs of searching, development, and/or commercialization among licensee types. Our work differs from theirs by explicitly linking the licensing terms (royalty rate and fixed fee) to inventor's likely ownership share in a start-up and to the resulting development efforts chosen by the inventor and licensee. This comprehensive approach reveals that under reasonable conditions, a lower royalty rate increases the inventor share of ownership in a start-up, resulting in more effort by both the inventor and licensee, thus making a start-up a more attractive licensee than an established firm.

While theoretical work on start-ups has been sparse, empirical work has been growing. Shane has examined factors influencing the performance of start-ups using data on inventions by MIT faculty. He shows that the formation of start-ups is fostered by both recognition of business opportunities by inventors (Shane 2000) and the presence of technological opportunities (Shane 2001). Shane and Stuart (2002) find that start-ups are more likely to succeed if the founders have relationships with venture capitalists. Lowe and Ziedonis (2004) compare licenses to start-ups with licenses to established firms using data from the University of California, and find that royalties from start-ups are higher, on average, but successful commercialization tends to occur only after acquisition of the start-up by an established firm. Belenzon and Schankerman (2009) examine the effects of licensing, university ownership, and local development objectives in technology transfer.[3] They find that incentive pay by university TTOs significantly increases income per license, and the presence of local development objectives increases the number of local start-ups, at a cost of lower income per license. State government controls (choice of licensee, contracting terms, equity stakes, etc.) tend to reduce license income and slow start-up formation. Along the same lines, our analysis describes a rationale for start-ups if equity stakes and contracting terms are not limited. Our work is also related to Di Gregorio and Shane (2003), who examine start-up formation across US universities using AUTM data for the period 1994-1998 and find a positive relationship between start-up formation and faculty quality. Our theoretical analysis lends support to this finding; in our model, we show that greater faculty quality will (*ceteris paribus*) cause a TTO to lean toward allowing a faculty inventor to find a venture capitalist to license the invention, where the ownership shares held by the faculty inventor create more combined effort.

[3] They develop a model of a TTO's choice between licensing to local versus national firms, subject to optimal inventor behavior, to examine the effects of TTO preference for local development. Although they empirically test licensing to startups, theie model makes no predictions for licensing to startups versus established firms.

Other recent literature has examined start-up firm activity and licensing in general. Shane and Somaya (2007) use AUTM data and patent litigation data during 1991-2000 to examine the effects of patent litigation on university licensing efforts. Siegel *et al.* (2008) examine the relationship between licenses, TTO staff, and legal expenditures in their analysis of university technology transfer. Feldman, Feller, Bercovitz and Burton (2002) find an increase in the use of cashed-in-equity in licensing agreements. The following analysis sets a theoretical foundation for many of these empirical studies, identifying factors that affect the type of firm that licenses university inventions.

3 The Model

The model is a reasonably straightforward compilation and extension of those in Jensen and Thursby (2001) and Jensen, Thursby, and Thursby (2003). We model the problem as a three-stage game with two distinct possibilities of interest: an invention commercialized by either an established firm or a start-up firm. The games have four players: the TTO, the inventor, an established firm, and a venture capitalist. In the first stage, the inventor discloses an invention to the TTO, who must determine whether to try to license the invention to an established firm, or to allow the inventor to seek a venture capitalist (or angel investor) to help form a start-up firm, which licenses the invention.[4] In addition, the TTO in the first stage must determine the terms of the licensing contract (royalties and fixed fee), which can differ depending on whether the licensee is an established firm or start-up firm. We assume all contracts are take-it-or-leave it offers.

In the second stage, the inventor negotiates its split of ownership shares with the venture capitalist if the licensee is a start-up firm. If the licensee is an established firm, the inventor cannot retain any ownership share and thus there is no second stage decision. The rationale is that established firms are more likely to be diversified in other product areas and any inventor effort will therefore have a smaller impact on share values compared to a single-product start-up; the weaker link between inventor effort and these share values will therefore cause firms to be less likely to offer shares as compensation.[5]

[4] Thus, we are assuming that the inventor does not have the financial wherewithal to pay the costs of commercialization associated with a startup, and so must seek a partner with the necessary financial resources.

[5] This approach to inserting a venture capitalist into the standard licensing model is similar to that used by deBettignies and Brander (2007), although here the approach is more general in that it doesn't rely on a specific function form.

In the third stage, the inventor and established firm or start-up firm choose a level of effort to increase the invention's probability of a success in development and commercialization, which is common knowledge after effort has been expended. If the expected return for the firm is positive, the firm then expends additional resources necessary to attempt to commercialize it; upon success, the firm produces and pays royalties to the TTO (since they still hold the patent in either case). If the invention fails, the game ends.

In order for the possibility of successful commercialization, whether by an established firm or start-up firm, development effort must be expended by both the inventor and the firm. We let e and v denote the total efforts expended by the inventor and the firm (for convenience, the 'firm' in our model will refer to the established firm or the start-up venture capitalist). We assume these efforts are not contractible, but instead are chosen at the beginning of the development period (after the licensing agreement has been made) and depend, in general, on the royalty rate and fixed fees in the contract, denoted by $[r, F]$.

As is well-known by now, university inventions are typically embryonic. Their commercial potential is uncertain, and the likelihood of their success is small. We assume that the probability of success $p(e, v)$ depends on the development efforts, which can be considered inputs in the "production" of a probability of success. We assume that p is nondecreasing in efforts, is jointly concave in all its arguments, and that $p \in (0, 1)$ for all (e, v). Finally, we assume that additional effort by the firm (in the form of more or better equipment, for example) should increase the marginal impact of inventor effort on the probability of success, $\frac{\partial^2 p}{\partial e \partial v} > 0$. That is, inventor and firm efforts are "complements" in development, in the sense that they complement each other in the production of a positive probability of success.

Suppose a firm (either a start-up or established firm) has licensed an invention, additional development has taken place, and the invention is a success. The licensee will then choose output to maximize its profit, net of any license fees. In general, because marginal production cost depends on the royalty rate, the firm's maximal output is decreasing in the royalty rate. Denote profit-maximizing output by $x(r)$ where $r \geq 0$ is the royalty rate per unit of output. Assume that $x(0) > 0$ and $x'(r) < 0$, and that total royalty revenue $R = rx(r)$ is strictly concave in r and has a unique maximum at a positive, finite value.[6] Assume also that the firm must pay a fixed license fee $F > 0$, and fixed cost of commercialization, $C > 0$, which could

[6] These assumptions on royalty revenue hold for a broad class of new process innovations licensed to a single firm (including, but not limited to, the case of linear demand and constant marginal cost).

take the form of adoption, installation or entry. These fixed costs are incurred whether or not the invention is successful. If $\pi(x(r))$ represents the profit (gross of any license fees) from producing x units from the invention, then the expected profit of the licensee is:

$$\Pi = p(e,v)[\pi(x(r)) - rx(r)] - C - F \tag{1}$$

We are assuming that inventions that are so embryonic that commercial success requires further development by the inventor, thus $p(0,0) = 0$ and $p \in [0,1)$ for all $e, v \geq 0$.

The efforts chosen by both the licensee and inventor depend on the split of ownership shares (if a start-up firm is the licensee) as well as the split of licensing revenue between the inventor and TTO. We assume that in the case of a start-up licensee, competition exists in the market for venture capital but the market for inventions is imperfect, thus the ownership split of the start-up is assumed to be chosen by the inventor. Let $\sigma \in [0,1]$ be the proportion of shares owned by the inventor and $(1-\sigma)$ be the proportion owned by the venture capitalist, where $\sigma = 0$ for the case of an established firm licensee. Also, university policies often stipulate that any license revenues earned are split in a predetermined proportion between the TTO and the faculty inventor. Let the proportion of licensing revenue that is paid to the inventor be $\alpha \in [0,1]$, and therefore $(1-\alpha)$ is the proportion retained to the university's TTO.

The expected income to the inventor is equal to the value of its ownership shares (σ) in the firm plus the split (α) of licensing revenue from the TTO, less search costs of finding a licensee (s):

$$I = \sigma\Pi + \alpha[F + p(e,v)rx(r)] - s \tag{2}$$

$$= \sigma[p(e,v)\pi(x(r)) - C] + (\alpha - \sigma)[p(e,v)rx(r) + F] - s \tag{3}$$

The second term of equation 3 illustrates the fact that in the case of a start-up, licensing fees flow in two directions: from the inventor as shareholder of the firm to the TTO, and also from the TTO back to inventor in the revenue-sharing agreement. The net licensing flows to the inventor may be positive or negative depending on the relative sizes of σ and α. If $\sigma > \alpha$, for instance, then licensing fees on balance flow out to the university. If $\sigma < \alpha$, then licensing fees flow in to the inventor. If $\sigma = \alpha$, then outflows equal inflows and the net effect is zero.

In order to consider the possibility of risk-aversion, we need to adjust (3) to examine the inventor's expected utility of income. To do so, we state the inventor income in the case of success:

$$I_s = \sigma[\pi(x(r)) - C] + (\alpha - \sigma)[rx(r) + F] - s \tag{4}$$

and in the case of failure:

$$I_f = \sigma(-C) + (\alpha - \sigma)F - s \tag{5}$$

Under invention success (4), the expected utility reflects shareholder profit before licensing fees ($\sigma[\pi(x(r)) - C]$) plus the net flow of licensing fees ($(\alpha - \sigma)[rx(r) + F]$). Under invention failure (5), inventor income reflects the negative shareholder return from the commercialization cost ($\sigma(-C)$) plus the net flow from the fixed licensing fee ($(\alpha - \sigma)F$). Note that the commercialization (C) and search costs (s) are therefore incurred in any case, and likewise the flow of funds from the fixed fee ($(\alpha - \sigma)F$) do not depend on success or failure.

The expected utility of inventor income is thus $p(e, v)\{I_s\} + (1 - p(e, v))\{I_f\}$:

$$\begin{aligned} P_I \quad = \quad & p(e, v)U\{\sigma[\pi(x(r)) - C] + (\alpha - \sigma)[rx(r) + F] - s\} \\ & +(1 - p(e, v))U\{\sigma(-C) + (\alpha - \sigma)F - s\} - c(e) \end{aligned} \tag{6}$$

where $c(e)$ represents the cost (disutility) of effort. Naturally we assume positive but nonincreasing marginal utility from income (so the inventor can be risk-neutral or risk-averse), and positive and non-decreasing marginal disutility of effort: $U' > 0 \geq U''$, $c' > 0$, and $c'' \geq 0$.

The payoff to the risk-neutral firm is the value of its ownership shares less costs of development effort:

$$
\begin{aligned}
P_M &= (1-\sigma)\Pi - c(v) & (7)\\
&= (1-\sigma)\{p(e,v)[\pi(x(r)) - rx(r)] - C - F\} - c(v) & (8)
\end{aligned}
$$

where $c' > 0$, and $c'' \geq 0$.

3.1 Effort and Production: Stage Three

As is standard, we begin by considering the final subgame, in which the inventor chooses the amount of effort e to expend on development in the attempt to bring the invention to commercialization, and the firm (established firm or venture capitalist) decides the level of resources v it commits to this development. In the final stage, the type of licensee and ownership share split have already been determined. The amount of effort the inventor can expend and the resources at the disposal of the firm are limited. We denote these upper bounds by E and V. Existence of a Nash equilibrium $(e^*(\sigma, \alpha, C, r, F), v^*(\sigma, \alpha, C, r, F))$ for this game then follows immediately from standard results. We are interested, of course, in when the equilibrium is interior, and how these equilibrium values vary with the parameters of interest. When the equilibrium is interior, it is characterized by $\frac{\partial P_I(e^*, v^*)}{\partial e} = 0$ and $\frac{\partial P_M(e^*, v^*)}{\partial v} = 0$ where

$$
\frac{\partial P_I}{\partial e} = \frac{\partial p}{\partial e} U(I_s) - \frac{\partial p}{\partial e} U(I_f) - c'(e) \tag{9}
$$

and

$$
\frac{\partial P_M}{\partial v} = \frac{\partial p}{\partial v}(1-\sigma)[\pi(x(r)) - rx(r)] - c'(v). \tag{10}
$$

Each player in the above first-order conditions increases effort until the marginal benefit of additional effort is just equal to marginal cost. A necessary condition for an interior equilibrium is that a successful invention will be profitable net of licensing payments, i.e. $\pi(x(r)) - rx(r) > 0$, because it ensures a positive marginal benefit of effort for both players.

If the contract is signed and production takes place, the firm chooses output x to maximize profit, $\pi(x(r)) - rx(r)$, of the firm. The first-order condition is:

$$\pi'(x(r)) - r = 0. \tag{11}$$

Firms therefore set marginal benefit of additional output equal to the marginal cost. We now turn to how efforts are affected by fixed fees, commercialization costs, the inventor's share of licensing revenue, and the inventor's ownership share:

Theorem 1 *Consider the strategic form game with the inventor and firm as players with strategies $e \in [0, E]$ and $v \in [0, V]$, and payoff functions are defined by (1)-(3). Also assume each player's payoff function is continuous and strictly quasi-concave in its own strategy, given any strategy choices by the other players. Then this game has a Nash equilibrium $(e^*(\sigma, \alpha, C, r, F), v^*(\sigma, \alpha, C, r, F))$. If, in addition, $\partial P_I(0, v)/\partial e > 0 > \partial P_I(E, v)/\partial e$ for all v and $\partial P_M(e, 0)/\partial v > 0 > \partial P_M(e, V)/\partial v$ for all e, then this equilibrium is interior,*[7] *and if it is also locally stable, then:*

(i) An increase in the commercialization cost or the fixed license fee has no effect on equilibrium efforts ($\frac{\partial e^*}{\partial j} = 0$ and $\frac{\partial v^*}{\partial j} = 0$ for $j = C, F$) if the inventor is risk-neutral. If the inventor is risk-averse, and if her share of license revenue exceeds her share of profit, $\alpha > \sigma$, then an increase in this cost or the fee decreases equilibrium efforts, $\frac{\partial e^*}{\partial j} < 0$ and $\frac{\partial v^*}{\partial j} < 0$ for $j = C, F$.

(ii) An increase in the inventor's share of license revenue increases equilibrium efforts ($\frac{\partial e^*}{\partial \alpha} > 0$ and $\frac{\partial v^*}{\partial \alpha} > 0$) if the inventor is risk-neutral or not too risk-averse.

(iii) An increase in the royalty rate decreases equilibrium efforts ($\frac{\partial e^*}{\partial r} < 0$ and $\frac{\partial v^*}{\partial r} < 0$) if total royalty income paid to the university is non-increasing in the royalty rate at equilibrium, or if her profit share exceeds her share of license revenue, $\sigma > \alpha$.

(iv) If the inventor is very risk-averse, then an increase in her profit share decreases equilibrium efforts ($\frac{\partial e^*}{\partial \sigma} < 0$ and $\frac{\partial v^*}{\partial \sigma} < 0$). Otherwise, an increase in her profit share shifts her reaction function out, but shifts the venture capitalist's reaction function in, and so in general has an ambiguous effect on equilibrium efforts. However, if she is risk-neutral, then sufficient conditions for an increase in her profit share to increase efforts ($\frac{\partial e^*}{\partial \sigma} > 0$ and $\frac{\partial v^*}{\partial \sigma} > 0$) are:

[7] *Note that $\frac{\partial P_I(0,v)}{\partial e} > 0$ if $\frac{\partial p(0,v)}{\partial e} > 0$ and $\pi(x(r)) > rx(r)$, and $\frac{\partial P_{VC}}{\partial v} > 0$ if $\frac{\partial p(e,0)}{\partial v} > 0$ and $\pi(x(r)) > rx(r)$, which are very reasonable conditions.*

a) the marginal effect of inventor effort on the probability of success is sufficiently large, $\frac{\partial p}{\partial e} > \max\{\frac{\partial^2 p}{\partial e \partial v}, \left|\frac{\partial^2 p}{\partial e^2}\right|\}$*;*

b) the marginal effect of venture capitalist effort on the probability of success is sufficiently small, $\left|\frac{\partial p}{\partial v}\right| < (1-\sigma)\min\{\left|\frac{\partial^2 p}{\partial v^2}\right|, \frac{\partial^2 p}{\partial v \partial e}\}$*; and*

c) her license revenue is less than the venture capitalist's profit net of license revenue, $\alpha r x(r) < (1-\sigma)(\pi(x(r)) - r x(r))$*.*

The key to understanding changes in equilibrium efforts is in the analysis of the shifts in reaction functions from changes in F, α, σ, r, and C. If the inventor is risk-neutral, then reaction functions of both firms are upward-sloping, indicating that equilibrium efforts are strategic complements (see figure 1). It is logical to reason that when investors are risk-neutral, changes in commercialization or fixed fees, because of their fixed nature, do not affect equilibrium effort.[8]

(figure 1 about here)

An increase in inventor's share of licensing income, α, directly affects only the inventor. If the inventor is risk-neutral (or not too risk-averse), the marginal benefit to the inventor of extra effort increases with α because the inventor is getting a larger proportion of the license revenue. The reaction function of the inventor shifts out, inducing a higher level of effort from the firm, and efforts rise in equilibrium. If the inventor is very risk-averse, however, then the negative 'income effect' may dominate. Here, a higher split of license revenue raises income, which lowers the marginal benefit of additional income (and effort); if large enough, this effect shifts the reaction function inward and induces a lower level of effort from the firm, and efforts fall in equilibrium.

If either royalty income is non-increasing in royalty rates or inventor ownership share is greater than inventor license revenue share ($\alpha < \sigma$), then an increase in the royalty rate (unless investor is very risk-averse) reduces efforts. An increase in the royalty rate under these circumstances reduces inventor income, which shifts its reaction function inward and induces a similar reduction in effort from the firm. Note that

[8] If the inventor is risk-averse, however, an increase in commercialization costs or fixed fees will lower inventor income, raising the marginal benefit of additional effort, shifting the reaction function of the inventor outward.

the assumption of royalty revenue being non-increasing in royalty rates is reasonable for higher royalty rates, where demand is elastic enough that production decreases significantly as the firm raises price of the good in response to those higher royalty rates.

An increase in ownership shares, σ, has an ambiguous effect on equilibrium efforts. Recall that ownership shares are only possible for the case of a start-up funded by a venture capitalist, VC (who is the 'firm' in this case). As σ increases, the inventor's marginal benefit of effort increases and the VC's marginal benefit of effort decreases because the inventor takes a larger split of the start-up profits at the expense of the VC. The reaction function of the inventor shifts out, while the venture capitalist's reaction function shifts in; thus, several possibilities exist for the equilibrium change in efforts. Figure 2 illustrates one such possibility: that both efforts rise in equilibrium. If inventor effort is very important to increasing probability of success relative to the firm's effort (large $\frac{\partial p}{\partial e}$ and small $\frac{\partial p}{\partial v}$), and inventor license revenue ($\alpha r x(r)$) is less than the venture capitalist's return net of license fees ($(1-\sigma)(\pi(x(r)) - rx(r))$), then efforts rise in equilibrium. A strong inventor effort effect, $\frac{\partial p}{\partial e}$, will cause a greater shift outward in the inventor's reaction function with an increase in ownership share, making the VC more likely to increase effort in equilibrium. Similarly, a weak VC effort effect, $\frac{\partial p}{\partial v}$, or small VC ownership share $(1-\sigma)$ mutes the VC effort response to smaller VC ownership, making equilibrium VC effort to more likely follow that of the inventor. Finally, if the inventor share of license revenues from the TTO, α, is small, then there is a smaller cross effect of VC effort on the inventor's marginal return from effort. If so, then a greater ownership share by the inventor will mute the negative effect of subsequent lower VC effort on the inventor's effort, and thus equilibrium efforts are more likely to rise.

(figure 2 about here)

3.2 Ownership Shares: Stage Two

In stage two, the inventor has a choice of ownership shares if the licensee is a start-up funded by a venture capitalist (if the licensee is an established firm, then the inventor gets no ownership). Given the equilibrium effort choices (from stage three), the inventor problem is to choose an ownership share σ that maximizes expected payoff:

$$\max_{\sigma} P_I = p(e^*, v^*)U\{I_s\} + (1 - p(e^*, v^*))U\{I_f\} - c(e^*) \tag{12}$$

subject to the participation constraint of the venture capitalist,

$$P_M = (1 - \sigma)\{p(e^*, v^*)[\pi(x(r)) - rx(r)] - C - F\} - c(v^*) \geq 0. \tag{13}$$

We assume that if $r = F = 0$, then $\Pi^* = p(e, v)\pi(x(0)) - C > 0$ for some effort levels, so development will occur. The Lagrangian function for the optimization problem is:

$$Z = P_I(e^*, v^*) + y[P_M(e^*, v^*)] \tag{14}$$

with resulting Kuhn-Tucker conditions $\partial Z/\partial\sigma \leq 0$, $\sigma \geq 0$, $\sigma(\partial Z/\partial\sigma) = 0$, $\partial Z/\partial y \geq 0$, $y \geq 0$, and $y(\partial Z/\partial y) = 0$. If the solution to the inventor's problem is interior and the constraint is nonbinding ($y = 0$), it is characterized by $\frac{\partial Z(e^*,v^*)}{\partial\sigma} = \frac{\partial P_I(e^*,v^*)}{\partial\sigma} = 0$, where:

$$\begin{aligned}\frac{\partial P_I(e^*, v^*)}{\partial\sigma} &= \{\frac{\partial p}{\partial e}\frac{\partial e^*}{\partial\sigma} + \frac{\partial p}{\partial v}\frac{\partial v^*}{\partial\sigma}\}[U\{I_s\} - U\{I_f\}] + \\ &\quad p(e^*, v^*)[U'\{I_s\}\frac{\partial I_s}{\partial\sigma} - U'\{I_f\}\frac{\partial I_f}{\partial\sigma}] + U'\{I_f\}\frac{\partial I_f}{\partial\sigma} - (\frac{\partial c}{\partial e}\frac{\partial e^*}{\partial\sigma})\end{aligned} \tag{15}$$

which implies an optimal σ^*. We assume an interior $\sigma^* \in (0, 1)$ solution hereafter. Note that $\sigma^* < 1$ because we have assumed the inventor cannot fund a start-up without a venture capitalist, who must have a positive share of profit to invest. For $\sigma^* > 0$, it is necessary that the inventor's initial profit share increases the expected utility of income (i.e., (15) is positive at $\sigma = 0$). Recalling Theorem 1, if the inventor is risk-neutral, for example, then this initial increase in ownership shares results in increased effort by both the inventor and the firm. This results in an increase in both the probability of success and the disutility of inventor effort. If the former effect outweighs the latter (as would be true if $c\prime(0) = 0$), and if P_I is quasi-concave in σ, then $\frac{\partial P_I(e^*,v^*)}{\partial \sigma} = 0$ at a $\sigma^* \in (0,1)$. This condition is only necessary for a contract with inventor ownership, of course, because the inventor's expected utility at σ^*must be non-negative (i.e., $P_I \geq 0$).

The following result indicates conditions under which inventor ownership is more likely, ceteris paribus.

Theorem 2 *Assume that inventor payoff, P_I, is quasi-concave in ownership share σ. A contract is more likely to be executed if:*

(i) the effort cost function of either player, $c(e)$ or $c(v)$, or the search cost, s, decrease;

(ii) the fixed fee, F, or commercialization cost, C, decrease; or,

(iii) the licensing revenue share, α, increases, given that the marginal effort costs of the inventor and venture capitalist are not too large.

A contract is more likely to be signed if the payoff to the inventor increases or if the venture capitalist's participation constraint is relaxed. If the cost of effort for the venture capitalist decreases, the participation constraint is relaxed and the contract is more likely. If search costs of the inventor fall, then the payoff function of the inventor increases, making it more likely that the inventor will search for a venture capitalist. Additional cost savings from the start-up, including fixed fees and commercialization costs, allow both the inventor payoff function to rise and the venture capitalist participation constraint to be relaxed, thus a contract agreement is more likely. An increase in licensing revenue share increases effort of both the inventor and venture capitalist (see theorem 1), increasing the probability of success; if the cost of the higher induced effort by the inventor is not too large, then efforts rise, payoffs rise, and a contract is more likely.

We now examine the effect of a change in royalty rates and fixed fees on the inventor's optimal ownership share σ^*, implicitly defined in an interior solution in (14). totally differentiating (14), we get:

$$\frac{\partial^2 P_I}{\partial \sigma \partial r} dr + \frac{\partial^2 P_I}{\partial \sigma^2} d\sigma^* + \frac{\partial^2 P_I}{\partial \sigma \partial F} dF = 0 \tag{16}$$

which implies:

$$\frac{d\sigma^*}{dr} = \frac{-\frac{\partial^2 P_I}{\partial\sigma\partial r}}{\frac{\partial^2 P_I}{\partial\sigma^2}} \tag{17}$$

and

$$\frac{d\sigma^*}{dF} = \frac{-\frac{\partial^2 P_I}{\partial\sigma\partial F}}{\frac{\partial^2 P_I}{\partial\sigma^2}} \tag{18}$$

Theorem 3 *Assume the inventor is risk-neutral or not too risk-averse, and equilibrium efforts are increasing in inventor's ownership share and decreasing in the royalty rate ($\frac{\partial e^*}{\partial\sigma} > 0$, $\frac{\partial v^*}{\partial\sigma} > 0$, $\frac{\partial e^*}{\partial r} < 0$, and $\frac{\partial v^*}{\partial r} < 0$). In an interior equilibrium, a greater royalty rate will reduce inventor's ownership share ($\frac{d\sigma^*}{dr} < 0$) if:*

i) the marginal effort cost is sufficiently small and rising sufficiently slowly (small $\frac{\partial c}{\partial e}$, $\frac{\partial c}{\partial v}$, $\frac{\partial^2 c}{\partial e^2}$, $\frac{\partial^2 c}{\partial v^2}$);

ii) the inventor share of license revenue (α) and ownership share (σ) are sufficiently small; and

iii) the firm's profit is not too large or small ($x(r) < \pi(x(r)) - rx(r) < 2x(r)$)

A higher royalty rate affects the choice of ownership shares two ways; directly through a reduction in inventor returns, and indirectly through lower combined effort. As for the direct effect, a higher royalty rate causes lower returns to the inventor through the split of licensing revenue (when royalty revenue is decreasing in the royalty rate, or when $\alpha < \sigma$) and also through the lower start-up profit. Thus, a higher royalty rate (under these conditions) reduces the benefit of taking additional ownership shares. As for the effort effect, a higher royalty rate (given the conditions of Theorem 1 and 3) reduces incentive to expend effort (see Theorem 1) and also the marginal ownership effect on effort, reducing the benefit of additional shares. The negative indirect effect is conditional upon a strong $\frac{\partial p}{\partial e}$, a weak $\frac{\partial p}{\partial v}$, a small and slowly rising effort cost, a relatively small inventor share of revenue (α) and ownership share (σ), and a reasonable firm profit. Under these conditions, total efforts in equilibrium move in tandem with inventor effort because the VC effort effect is muted. Therefore, an inventor will respond to higher royalty rates by reducing effort, causing both efforts to fall in equilibrium, thus reducing the ownership share chosen.

We now turn to the stage one contracting decision.

3.3 License Contract: Stage One

In the first stage, the TTO chooses the license contract terms (royalty rate and fixed fee) that the firm will pay in order to acquire the rights to the invention. The TTO knows that these contract terms will affect the downstream decisions of the inventor and firm, including the ownership shares by the inventor (in a start-up) and development efforts by both the inventor and firm. Assume the TTO's objective is to maximize T, university net revenue (licensing revenue minus search costs, w), subject to the participation constraints of both the inventor and firm. If so, the TTO chooses r and F to:

$$\max_{r,F} T = (1-\alpha)[F + p\{e^*(\cdot), v^*(\cdot)\} r x(r)] - w \tag{19}$$

$$\text{subject to } P_I^* = p\{e^*(\cdot), v^*(\cdot)\} U(I_s(r,F)) - (1 - p\{e^*(\cdot), v^*(\cdot)\}) - c(e^*(\cdot)) - s \geq 0 \tag{20}$$

$$\text{and } P_M^* = [1 - \sigma^*(r,F)] \Pi^*(e^*(\cdot), v^*(\cdot), r, F) - c(v^*(\cdot)) \geq 0 \tag{21}$$

where e^* and v^* (in the suppressed arguments above) are a function of r, F, and $\sigma^*(r,F)$. If the TTO leaves the search to the inventor, then the TTO has no search costs ($w = 0$). If the TTO searches for an established firm, then the inventor has no search costs ($s = 0$). The The Lagrangian function for the optimization problem is:

$$L = T(e^*(\cdot), v^*(\cdot)) + \lambda_1[P_I^*(e^*(\cdot), v^*(\cdot))] + \lambda_2[P_M^*(e^*(\cdot), v^*(\cdot))] \tag{22}$$

with resulting Kuhn-Tucker conditions $\partial L/\partial F \leq 0$, $\partial L/\partial r \leq 0$, $F \geq 0$, $r \geq 0$, $\lambda_1 \geq 0$, $\lambda_2 \geq 0$, $r(\partial L/\partial r) = 0$, $F(\partial L/\partial F) \geq 0$, $\lambda_1(\partial L/\partial \lambda_1) = 0$, and $\lambda_2(\partial L/\partial \lambda_2) = 0$. If the solution to the inventor's problem is interior and the constraints are non-binding ($\lambda_1 = \lambda_1 = 0$), it is characterized by $\frac{\partial L(e^*,v^*)}{\partial r} = \frac{\partial T(e^*,v^*)}{\partial r} = 0$, where:

$$
\begin{aligned}
\frac{\partial T(e^*, v^*)}{\partial r} &= (1-\alpha)[\{\frac{\partial p}{\partial e}\frac{\partial e^*}{\partial r} + \frac{\partial p}{\partial e}\frac{\partial e^*}{\partial \sigma}\frac{\partial \sigma^*}{\partial r} + \frac{\partial p}{\partial v}\frac{\partial v^*}{\partial r} + \frac{\partial p}{\partial e}\frac{\partial v^*}{\partial \sigma}\frac{\partial \sigma^*}{\partial r}\}rx(r) \\
&\quad + p(e^*(\cdot), v^*(\cdot))(x(r) + rx'(r))] \qquad (23)
\end{aligned}
$$

and by $\frac{\partial L(e^*,v^*)}{\partial F} = \frac{\partial T(e^*,v^*)}{\partial F} = 0$, where:

$$
\frac{\partial T(e^*, v^*)}{\partial F} = (1-\alpha)[1 + \{\frac{\partial p}{\partial e}\frac{\partial e^*}{\partial F} + \frac{\partial p}{\partial e}\frac{\partial e^*}{\partial \sigma}\frac{\partial \sigma^*}{\partial F} + \frac{\partial p}{\partial v}\frac{\partial v^*}{\partial F} + \frac{\partial p}{\partial e}\frac{\partial v^*}{\partial \sigma}\frac{\partial \sigma^*}{\partial F}\}rx(r)] \qquad (24)
$$

which implies an optimal r^* and F^*. The next theorem describes the differences in optimal rates (royalty and fixed fees) between a license to a start-up and to an established firm.

Theorem 4 *Suppose the inventor is risk-neutral or not too risk averse, royalty revenue is either non-increasing or increasing slowly in the royalty rate, and an increase in the royalty rate decreases optimal ownership share($\partial\sigma^*/\partial r$). Then:*

(i) If the constraints are non-binding ($\lambda_1 = \lambda_2 = 0$), then given otherwise equal licensees, the TTO will choose a lower royalty rate and fixed fee for a start-up licensee than for an established firm.

(ii) If the inventor's participation constraint is binding ($\lambda_1 > 0$), the TTO will still choose a lower royalty rate and fixed fee for a start-up licensee if the additional effort disutility and greater loss under failure for the inventor is more than offset by the higher total effort effect on the probability of success and the greater expected gain to the firm's returns from success.

(iii) If the firm's participation constraint is binding ($\lambda_2 > 0$), the TTO will still choose a lower royalty rate and fixed fee for a start-up licensee if the decreased ownership effect of the firm from a lower royalty rate is small relative to the increased effort effect on the probability of success and the increased firm profit effect.

Theorem 4 shows that the relative importance of inventor and venture capitalist effort greatly affects the ownership share that is taken by the inventor, and also the return to the TTO. A change in the royalty rate affects effort two ways: directly through the change in income flows from ownership and licensing, and indirectly through the effect of the change in ownership shares. If inventor effort is very important relative to venture capital effort, and either royalty revenues decline in the royalty rate or $\sigma > \alpha$, then the direct effect is that higher royalty rates cause lower revenues flowing back to the inventor from the university, and also lower profits from the start-up. The indirect effect of higher royalty payments is a lower marginal benefit of additional shares in the start-up for the inventor, causing the inventor to reduce its share, further reducing effort. The venture capitalist follows with a lower effort level, causing the probability of success of the start-up to fall, reducing returns to the TTO. Thus, a lower royalty rate for a start-up will create additional effort (from both the inventor and the firm) through a greater ownership share of the inventor (second and fourth terms in 23). So, if the direct effect of a lower royalty rate on TTO revenue is small or negative, then evaluated at the optimal royalty rate for an established firm, $\frac{\partial T(e^*,v^*)}{\partial r} < 0$ for a start-up because $\frac{\partial \sigma}{\partial r} < 0$, causing the second an fourth terms in the braces of (23) to be negative (these terms are zero for an established firm license because the inventor cannot take ownership shares).

A lower royalty rate will also relax the participation constraint of the inventor ($\frac{\partial^2 L}{\partial \lambda_1 \partial r} = \frac{\partial P_I^*}{\partial r} < 0$) if costs of additional inventor effort are not too high. For the inventor, a lower royalty rate a) decreases the marginal cost of production from a shareholder perspective, b) increases royalty revenue from the revenue-sharing perspective, and c) increases effort, which increases the probability of success. For the firm, a lower royalty rate a) decreases the marginal cost of production and b) increases effort of both the inventor and firm, increasing the probability of success, but 3) also induces the inventor to choose a higher ownership share, reducing the share left for the firm. As long as the increased effort is strong relative to the lost ownership shares, the firm's participation constraint is relaxed. Thus, a lower royalty rate will relax the participation constraint of the firm ($\frac{\partial^2 L}{\partial \lambda_2 \partial r} = \frac{\partial P_M^*}{\partial r} < 0$) if costs of additional firm effort are not too high, and if the reduced ownership effect is outweighed by the greater effort effect.

For fixed fees, the intuition behind theorem 4 is that a lower fixed fee in the case of a start-up licensee will increase the marginal gain to the inventor from additional ownership shares, inducing the inventor to take more shares, thereby creating more effort by both the inventor and the firm. For the established firm licensee, the effect of fixed fees on ownership shares is zero; for the start-up licensee, it is negative. Thus, evaluated at the optimal fixed fee for an established firm licensee, $\frac{\partial T(e^*,v^*)}{\partial F} < 0$ for a start-up because $\frac{\partial \sigma}{\partial F} < 0$, causing the second an fourth terms in the braces of (24) to be negative. If the participation constraint of the inventor is binding, then a lower fixed fee will relax the constraint ($\frac{\partial^2 L}{\partial \lambda_1 \partial F} = \frac{\partial P_I^*}{\partial F} < 0$) if the inventor has a greater share of ownership than split of licensing revenues ($\alpha < \sigma$). If the licensing revenue split is high relative to the ownership share, then the lower fixed fee may reduce the inventor's overall profit, possibly inducing a contract refusal. If the participation constraint of the firm is binding, a lower fixed fee will in any case relax it ($\frac{\partial^2 L}{\partial \lambda_2 \partial F} = \frac{\partial P_M^*}{\partial F} < 0$) since $\frac{\partial P_M^*}{\partial F} = -(1-\sigma)$.

In the first stage, the TTO must determine not only what license contract terms to offer either a start-up or an established firm, but also whether to target an established firm or a start-up as a licensee. It knows that the contract terms will affect ownership split (in the case of a start-up) and downstream efforts, so it chooses those optimally, maximizing profit while inducing participation from the other parties. The initial decision of whom to target boils down to which licensee generates a higher TTO payoff. The TTO will thus choose to target a start-up (that is, shelve the invention and allow the inventor to search for a start-up) if: .

$$\begin{aligned} T_\rho &= (1-\alpha)[F_\rho^* + p\{e^*(r_\rho^*, F_\rho^*, \sigma^*(r_\rho^*, F_\rho^*)), v^*(r_\rho^*, F_\rho^*, \sigma^*(r_\rho^*, F_\rho^*))\}r_\rho^* x^*(r_\rho^*)] \\ &> T_\mu = (1-\alpha)[F_\mu^* + p\{e^*(r_\mu^*, F_\mu^*), v^*(r_\mu^*, F_\mu^*)\}r_\mu^* x^*(r_\mu^*)] - w \end{aligned} \tag{25}$$

where ρ represents a start-up licensee and μ represents an established firm licensee, and T_ρ and T_μ solve the optimization problems in 23 and 24.

Theorem 5 *Given otherwise equal licensees, the TTO is more likely to license to a start-up if:*

(i) the search cost of the inventor, s, decreases,

(ii) the search cost of the TTO, w, increases, or

(iii) the inventor's effort effect on the probability of success is very important relative to the firm's effort, so that $\frac{\partial e^*}{\partial \sigma} > 0$, $\frac{\partial v^*}{\partial \sigma} > 0$, and thus $\frac{\partial \sigma^*}{\partial r} < 0$

In fact, suppose the TTO return from a start-up (T_ρ) and an established firm (T_μ) are the same, each evaluated at the (same) royalty rate that maximizes (T_μ). If, in addition, the inventor is risk-neutral, constraints are non-binding ($\lambda_1 = \lambda_1 = 0$) at the optimum, royalty revenue is non-increasing or increasing *slowly in the royalty rate, and an increase in the royalty rate decreases optimal ownership share ($\frac{\partial \sigma^*}{\partial r} < 0$), then the TTO will choose to license to a start-up rather than an established firm ($T_\rho > T_\mu$) and will use a lower royalty rate than for an established firm license.*

The intuition for this result lies in the effect of royalty rate changes on ownership shares, and the subsequent effect of ownership shares on total effort. Recall that $\frac{\partial \sigma^*}{\partial r} < 0$ exists if inventor effort is significantly more important than venture capital effort. If inventor effort is very important, additional ownership shares from lower royalty rates greatly increase the marginal benefit from extra effort through an increase in the probability of success on expected start-up returns. Thus the inventor is likely to significantly raise effort with higher ownership share. Whether the venture capitalist also raises effort depends on the balance of the complementary cross-effect of higher inventor effort (which raises venture capital effort) and the direct effect of lower venture capital ownership share (which lowers venture capital effort). If the venture capitalist effort is not very important, then the decline in the venture capital ownership share has little effect on effort, thus the complementary cross-effect of higher inventor effort is likely greater than the direct ownership share effect, and the venture capitalist increases effort in response to lower ownership share. The TTO, then, must weigh the greater effort and profit from a start-up with the extra search costs of the inventor in finding the start-up; if those costs are too high, then $P_I < 0$ and the inventor will not sign a contract. Given otherwise equal licensees and if higher royalty rates decreases ownership share and royalty revenue, a TTO (in an interior equilibrium) will license to a start-up rather than an established firm, and will use lower royalty rates. A lower royalty rate increases effort through the ownership channel ($\frac{\partial p}{\partial e} \frac{\partial e^*}{\partial \sigma} \frac{\partial \sigma^*}{\partial r}$ in (25)) in a start-up, raising TTO returns from a start-up relative to an established firm.

4 Conclusion

The choice between an established firm and a start-up has significant effects on inventor effort and therefore probable success of the invention. The use of start-up firms to commercialize university inventions is more common in situations in which the quality level of the faculty is high relative to the firm or the cost of searching for an established firm relative to a start-up is higher. The use of a start-up has the advantage of allowing the faculty inventor to hold ownership shares, which induces greater subsequent development effort than would be the case under an established firm. If the cost of searching for a start-up is not too high relative to the gains from greater effort, the TTO will shelve the invention and allow the inventor to search for a start-up. Future work includes an empirical examination of the factors that influence start-up formation, as well as an incorporation of varying forms of equity ownership among the TTO, inventor, and start-up.

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Proofs

Proof. : Theorem 1

Because the number of players is finite, their strategy sets are compact and nonempty, and their payoff functions are continuous and strictly quasi-concave, this follows directly from the well-known existence theorem for strategic form games with continuous strategy spaces (see, for example, Friedman 1977). Using standard comparative statics analysis, $\frac{\partial e^*}{\partial j} = [\frac{\partial^2 P_I}{\partial e \partial v}\frac{\partial^2 P_M}{\partial v \partial j} - \frac{\partial^2 P_M}{\partial v^2}\frac{\partial^2 P_I}{\partial e \partial j}]/D$ and $\frac{\partial v^*}{\partial j} = [\frac{\partial^2 P_M}{\partial v \partial e}\frac{\partial^2 P_I}{\partial e \partial j} - \frac{\partial^2 P_I}{\partial e^2}\frac{\partial^2 P_M}{\partial v \partial j}]/D$, for $j = F, C, \alpha, r, \sigma$ where $D = \frac{\partial^2 P_I}{\partial e^2}\frac{\partial^2 P_M}{\partial v^2} - \frac{\partial^2 P_I}{\partial e \partial v}\frac{\partial^2 P_M}{\partial v \partial e} > 0$ by the assumption that the equilibrium is locally stable.

The effect of an increase in firm effort on the inventor's marginal payoff from effort is $\frac{\partial^2 P_I}{\partial e \partial v} = \frac{\partial^2 p}{\partial e \partial v}[U\{I_s\} - U\{I_f\}] - \frac{\partial^2 c}{\partial e \partial v}$, which is positive because of a) the assumption of strategic complementarity in efforts ($\frac{\partial^2 p}{\partial e \partial v} > 0$), b) $U\{I_s\} > U\{I_f\}$ which holds in an interior equilibrium, and c) inventor effort does not increase the marginal disutility of inventor effort, $\frac{\partial^2 c}{\partial e \partial v} \leq 0$.

The effect of an increase in inventor effort on the firm's marginal payoff from effort is $\frac{\partial^2 P_M}{\partial v \partial e} = \frac{\partial^2 p}{\partial v \partial e}(1 - \sigma)[\pi(x(r)) - rx(r)] - \frac{\partial^2 c}{\partial v \partial e}$, which is positive assuming an interior equilibrium ($\pi(x(r)) - rx(r) > 0$) and if $\sigma < 1$, because $\frac{\partial^2 p}{\partial v \partial e} > 0$ (strategic complementarity), and effort of the inventor does not increase the marginal cost of the firm ($\frac{\partial^2 c}{\partial v \partial e} \leq 0$). We are now ready to consider the effect of variables $F, C, \alpha, r,$ and σon equilibrium efforts of the inventor and firm:

(i) The effect of an increase in the fixed fee on inventor's marginal payoff from effort is $\frac{\partial^2 P_I}{\partial e \partial F} = (\alpha - \sigma)\frac{\partial p}{\partial e}[U'\{I_s\} - U'\{I_f\}]$, which is zero under risk-neutrality (constant U'). It is negative under risk-aversion if $(\alpha - \sigma) > 0$ and $\pi(x(r)) - rx(r) > 0$, and because $U'\{I_s\} < U'\{I_f\}$. an increase in the fixed fee has no effect on the firm's marginal payoff from effort ($\frac{\partial^2 P_M}{\partial v \partial F} = 0$), thus $\frac{\partial e^*}{\partial F} = 0$ under risk-neutrality. Under risk-aversion, $\frac{\partial e^*}{\partial F} < 0$ if $(\alpha - \sigma) > 0$ because $U'\{I_s\} < U'\{I_f\}$.

For the effect on the firm's equilibrium effort, note that $\frac{\partial v^*}{\partial F} = 0$ in the risk-neutral case because $\frac{\partial^2 P_M}{\partial v \partial e} > 0$, $\frac{\partial^2 P_I}{\partial e \partial F} = 0$ (under risk neutrality), $\frac{\partial^2 P_I}{\partial e^2} < 0$, and $\frac{\partial^2 P_M}{\partial v \partial F} = 0$. In the risk-averse case where $\frac{\partial^2 P_I}{\partial e \partial F} < 0$, the firm's effort decreases in the fixed fee ($\frac{\partial v^*}{\partial F} < 0$).

The effect of an increase in commercialization cost on inventor's marginal payoff from effort is $\frac{\partial^2 P_I}{\partial e \partial C} = (-\sigma)\frac{\partial p}{\partial e}[U'\{I_s\} - U'\{I_f\}]$, which is zero under risk-neutrality, and is negative under risk-aversion (in an interior equilibrium) for the same reasons stated in (i). The effect of an increase in the fixed fee on the firm's marginal effort is $\frac{\partial^2 P_M}{\partial v \partial C} = 0$, thus $\frac{\partial e^*}{\partial C} = 0$ under risk-neutrality, and $\frac{\partial e^*}{\partial F} < 0$ under risk-aversion (given $(\alpha - \sigma) > 0$ and $\pi(x(r)) - rx(r) > 0$).

For the effect on the firm's equilibrium effort, note that $\frac{\partial v^*}{\partial F} = 0$ in the risk-neutral case because $\frac{\partial^2 P_M}{\partial v \partial e} > 0$, $\frac{\partial^2 P_I}{\partial e \partial C} = 0$ (under risk-neutrality), $\frac{\partial^2 P_I}{\partial e^2} < 0$, and $\frac{\partial^2 P_M}{\partial v \partial C} = 0$. Under risk-aversion where $\frac{\partial^2 P_I}{\partial e \partial C} < 0$, the firm's effort decreases in the commercialization cost ($\frac{\partial v^*}{\partial C} < 0$).

(ii) The effect of an increase in inventor's share of licensing fees on inventor's marginal payoff from effort is $\frac{\partial^2 P_I}{\partial e \partial \alpha} = \frac{\partial p}{\partial e}[\{rx(r) + F\}U'\{I_s\} - FU'\{I_f\}]$, which is positive under risk-neutrality since $U'\{I_s\} = U'\{I_f\}$. Under risk-aversion, the sign of $\frac{\partial^2 P_I}{\partial e \partial \alpha}$ is ambiguous because $U'\{I_s\} < U'\{I_f\}$ and $\{rx(r) + F\} > F$. A sufficient condition for $\frac{\partial^2 P_I}{\partial e \partial \alpha} > 0$ is $rx(r) > (\frac{F}{U'(I_s)})[U'\{I_f\} - U'\{I_s\}]$. The effect of an increase in inventor's share of licensing fees on the firm's marginal payoff from effort is $\frac{\partial^2 P_M}{\partial v \partial \alpha} = 0$. Under risk-neutrality, then, $\frac{\partial e^*}{\partial \alpha} > 0$. As long as the inventor is not too risk averse (i.e., where $rx(r) > (\frac{F}{U'(I_s)})[U'\{I_f\} - U'\{I_s\}]$, then $\frac{\partial e^*}{\partial \alpha} > 0$ also.

For the effect on the firm's equilibrium effort, $\frac{\partial v^*}{\partial \alpha} > 0$ in the risk-neutral case because $\frac{\partial^2 P_M}{\partial v \partial e} > 0$, $\frac{\partial^2 P_I}{\partial e \partial \alpha} > 0$ (under risk-neutrality), $\frac{\partial^2 P_I}{\partial e^2} < 0$, and $\frac{\partial^2 P_M}{\partial v \partial \alpha} = 0$. Under risk-aversion, $\frac{\partial v^*}{\partial \alpha} > 0$ if the inventor is not too risk-averse ($rx(r) > (\frac{F}{U'(I_s)})[U'\{I_f\} - U'\{I_s\}]$).

(iii) The effect of a royalty rate increase on the inventor's marginal effort is $\frac{\partial^2 P_I}{\partial e \partial r} = \frac{\partial p}{\partial e} U'\{I_s\}[\sigma\{\pi'(x'(r)) - rx'(r)\} + \alpha\{x(r) + rx'(r)\} - \sigma x(r)]$. Note that from the envelope theorem, $\pi' = r$, which implies that the first term in the braces, $\pi'(x'(r)) - rx'(r)$, is zero. Since $\frac{\partial p}{\partial e} > 0$ and $U'\{I_s\} > 0$, the remaining terms in the brackets, $\alpha\{x(r) + rx'(r)\} - \sigma x(r)$, determine the sign of $\frac{\partial^2 P_I}{\partial e \partial r}$. The remaining terms are positive if royalty income is increasing in the royalty rate ($x(r) + rx'(r) > 0$) and if $\alpha > \sigma$; under these conditions, then, $\frac{\partial^2 P_I}{\partial e \partial r} > 0$. If $x(r) + rx'(r) < 0$, or if $\alpha < \sigma$, then $\frac{\partial^2 P_I}{\partial e \partial r} < 0$. The effect of an increase in the royalty rate on the firm's marginal effort is $\frac{\partial^2 P_M}{\partial v \partial r} = \frac{\partial p}{\partial v}(1 - \sigma)[\pi'(x'(r)) - \{x(r) + rx'(r)\}]$, which is negative if $\sigma < 1$; note that from the envelope theorem, $\pi' = r$, which implies that the first and last terms in the brackets cancel, leaving $-x(r) < 0$. Thus, $\frac{\partial e^*}{\partial r} < 0$ if $x(r) + rx'(r) < 0$, or if $\alpha < \sigma$.

For the effect on the firm's equilibrium effort, note that $\frac{\partial^2 P_M}{\partial v \partial e} > 0$, $\frac{\partial^2 P_I}{\partial e^2} < 0$ and $\frac{\partial^2 P_M}{\partial v \partial r} < 0$, thus $\frac{\partial v^*}{\partial r} < 0$ if $\frac{\partial^2 P_I}{\partial e \partial r} < 0$.

(iv) The effect of increasing ownership share on the inventors's marginal payoff from effort is $\frac{\partial^2 P_I}{\partial e \partial \sigma} = \frac{\partial p}{\partial e}\{U'\{I_s\}[\pi(x(r)) - C - rx(r) - F] - U'\{I_f\}[-C - F]\}$, which is positive under risk-neutrality because $U'\{I_s\} = U'\{I_f\}$ and $\pi(x(r)) - rx(r) > 0$ in an interior equilibrium. Under risk-aversion, $\frac{\partial^2 P_I}{\partial e \partial \sigma} > 0$ if $U'\{I_f\} - U'\{I_s\} < \pi(x(r)) - rx(r)$ (i.e., if the inventor is not too risk-averse). The effect of increasing inventor ownership share on the firm's marginal payoff from effort is $\frac{\partial^2 P_M}{\partial v \partial \sigma} = -\frac{\partial p}{\partial v}[\pi(x(r)) - rx(r)]$, which is negative in an interior equilibrium. Thus, the sign of $\frac{\partial e^*}{\partial \sigma}$ is generally ambiguous unless the inventor is very risk-averse (in which case $\frac{\partial^2 P_I}{\partial e \partial \sigma} < 0$ and thus $\frac{\partial e^*}{\partial \sigma} < 0$). Despite this ambiguity, we can determine some conditions under which $\frac{\partial e^*}{\partial \sigma} > 0$. Recall that $\frac{\partial e^*}{\partial \sigma} = [\frac{\partial^2 P_I}{\partial e \partial v}\frac{\partial^2 P_M}{\partial v \partial \sigma} - \frac{\partial^2 P_M}{\partial v^2}\frac{\partial^2 P_I}{\partial e \partial \sigma}]/D$, where $D > 0$. Given $\frac{\partial^2 P_I}{\partial e \partial \sigma} > 0$, the last multiplicative term in the brackets, $-\frac{\partial^2 P_M}{\partial v^2}\frac{\partial^2 P_I}{\partial e \partial \sigma}$, gets more positive as $\frac{\partial p}{\partial e}$ gets larger, which increases $\frac{\partial e^*}{\partial \sigma}$. The first multiplicative term in the brackets, $\frac{\partial^2 P_I}{\partial e \partial v}\frac{\partial^2 P_M}{\partial v \partial \sigma}$, gets less negative as $\frac{\partial p}{\partial v}$ gets smaller, which also increases $\frac{\partial e^*}{\partial \sigma}$. In fact, sufficient conditions for $\frac{\partial e^*}{\partial \sigma} > 0$ are (a) $\frac{\partial^2 P_I}{\partial e \partial \sigma} > \frac{\partial^2 P_I}{\partial e \partial v}$, which is true under risk-neutrality if $\frac{\partial p}{\partial e} > \frac{\partial^2 p}{\partial e \partial v}$, and (b) $\left|\frac{\partial^2 P_M}{\partial v^2}\right| > \left|\frac{\partial^2 P_M}{\partial v \partial \sigma}\right|$, which is true if $\left|\frac{\partial^2 p}{\partial v^2}\right|(1-\sigma) > \left|\frac{\partial p}{\partial v}\right|$. (Condition (a) is actually $\frac{\partial p}{\partial e} > \frac{\partial^2 p}{\partial e \partial v}U_\phi$, where $U_\phi = (\frac{U(I_s) - U(I_f)}{U'(I)[\pi(x(r)) - rx(r)]})$. However, $U_\phi < 1$ if $\alpha rx(r) < (1-\sigma)(\pi(x(r)) - rx(r))$. This is because the denominator of U_ϕ can be written as $\frac{U(\pi(x(r)) - rx(r)}{\pi(x(r)) - rx(r)}(\pi(x(r)) - rx(r)) = U(\pi(x(r)) - rx(r))$. Then, the numerator of U_ϕ is less than the denominator (i.e. $U(\sigma\{\pi(x(r)) - rx(r)\} + \alpha rx(r)) < U(\pi(x(r)) - rx(r)))$ if $\alpha rx(r) < (1-\sigma)(\pi(x(r)) - rx(r)))$.

For the firm, the term $\frac{\partial v^*}{\partial \sigma} = [\frac{\partial^2 P_M}{\partial v \partial e}\frac{\partial^2 P_I}{\partial e \partial \sigma} - \frac{\partial^2 P_I}{\partial e^2}\frac{\partial^2 P_M}{\partial v \partial \sigma}]/D$. If the inventor is very risk-averse (in which case $\frac{\partial^2 P_I}{\partial e \partial \sigma} < 0$ and thus $\frac{\partial e^*}{\partial r} < 0$), then $\frac{\partial v^*}{\partial \sigma} < 0$. If not, then $\frac{\partial v^*}{\partial \sigma}$ is ambiguous; however, the last multiplicative term in the brackets, $-\frac{\partial^2 P_I}{\partial e^2}\frac{\partial^2 P_M}{\partial v \partial \sigma}$, gets less negative as $\frac{\partial p}{\partial v}$ gets smaller in absolute value, while the first (positive) term, $\frac{\partial^2 P_M}{\partial v \partial e}\frac{\partial^2 P_I}{\partial e \partial \sigma}$, grows as $\frac{\partial p}{\partial e}$gets larger. These conditions increase the likelihood that $\frac{\partial v^*}{\partial \sigma} > 0$. In particular, if $\frac{\partial^2 P_M}{\partial v \partial e} > \left|\frac{\partial^2 P_M}{\partial v \partial \sigma}\right|$ and $\frac{\partial^2 P_I}{\partial e \partial \sigma} > \left|\frac{\partial^2 P_I}{\partial e^2}\right|$, then $[\frac{\partial^2 P_M}{\partial v \partial e}\frac{\partial^2 P_I}{\partial e \partial \sigma} - \frac{\partial^2 P_I}{\partial e^2}\frac{\partial^2 P_M}{\partial v \partial \sigma}] > 0$ and thus $\frac{\partial v^*}{\partial \sigma} > 0$.

First, $\frac{\partial^2 P_M}{\partial v \partial e} = \frac{\partial^2 p}{\partial v \partial e}(1-\sigma)[\pi(x(r)) - rx'(r)] > \left|\frac{\partial^2 P_M}{\partial v \partial \sigma}\right| = \frac{\partial p}{\partial v}[\pi(x(r)) - rx(r)]$ if $\frac{\partial^2 p}{\partial v \partial e}(1-\sigma) > \frac{\partial p}{\partial v}$. Last, $\frac{\partial^2 P_I}{\partial e \partial \sigma} > \left|\frac{\partial^2 P_I}{\partial e^2}\right| = -\frac{\partial^2 p}{\partial e^2}(U\{I_f\} - U\{I_s\})$ if $\frac{\partial p}{\partial e} > \left|\frac{\partial^2 p}{\partial e^2}\right|$ and if $\alpha < (1-\sigma)(\frac{\pi(x(r))}{rx(r)} - 1)$ from above. ■

Proof. : Theorem 2

Venture capitalist payoff decreases in $c(v)$, i.e. $\frac{\partial P_M}{\partial c(v)} < 0$, thus a decrease in $c(v)$ causes a relaxation in the participation constraint, making a contract execution more likely. Also, inventor payoff decreases in $c(e)$, i.e.$\frac{\partial P_{FM}}{\partial c(v)} < 0$, thus a decrease in $c(e)$ causes inventor payoff to rise, increasing the likelihood that $P_I \geq 0$. Further, $\frac{\partial P_I}{\partial C}$, $\frac{\partial P_I}{\partial F}$, $\frac{\partial P_M}{\partial C}$, and $\frac{\partial P_M}{\partial F}$ are all negative, thus a reduction in either C or F causes both the payoff function of the inventor to rise and the venture capital constraint to be relaxed.

The effect of a change in inventor share of license fees on inventor payoff is $\frac{\partial P_I}{\partial \alpha} = [\frac{\partial p}{\partial e}\frac{\partial e^*}{\partial \alpha} + \frac{\partial p}{\partial v}\frac{\partial v^*}{\partial \alpha}][U\{I_s\} - U\{I_f\}] + p(e,v)\frac{\partial I_s}{\partial \alpha}[U'\{I_s\} - U'\{I_f\}] + U'\{I_f\}$, which is positive under risk-neutrality or if the inventor is not too risk averse because $\frac{\partial e^*}{\partial \alpha} > 0$ and $\frac{\partial v^*}{\partial \alpha} > 0$ (from Theorem 1); $\frac{\partial I_s}{\partial \alpha} = rx(r) + F > 0$; $I_s > I_f$ and thus $U\{I_s\} - U\{I_f\}$; $U'\{I_f\} > 0$; and $U'\{I_s\} - U'\{I_f\}$ is zero under risk-neutrality and negative but small if the inventor is not too risk-averse. Thus, under these conditions, an increase in inventor share of license fees raises inventor payoff at any ownership level, making contract execution more likely. The effect of inventor share of license fees on venture capital payoff is $\frac{\partial P_M}{\partial \alpha} = (1-\sigma)\{\frac{\partial p}{\partial e}\frac{\partial e^*}{\partial \alpha} + \frac{\partial p}{\partial v}\frac{\partial v^*}{\partial \alpha}\}(\pi(x(r)) - rx(r))$, which is also positive under the conditions stated for $\frac{\partial P_I}{\partial \alpha}$. Thus, an increase in inventor share of license fees raises inventor payoff and relaxes the participation constraint of the venture capitalist, increasing the likelihood of contract execution. ∎

Proof. : Theorem 3

Because of quasi-concavity, $\frac{\partial^2 P_I}{\partial \sigma^2} \leq 0$. If $\frac{\partial^2 P_I}{\partial \sigma^2}$ is strictly negative, then the sign of $\frac{d\sigma^*}{dr}$ is the same as the sign of $\frac{\partial^2 P_I}{\partial \sigma \partial r}$. Using (15), $\frac{\partial^2 P_I}{\partial \sigma \partial r} = [\frac{\partial p}{\partial e}\frac{\partial^2 e^*}{\partial \sigma \partial r} + \frac{\partial p}{\partial v}\frac{\partial^2 v^*}{\partial \sigma \partial r}][U\{I_s\} - U\{I_f\}] + [\frac{\partial p}{\partial e}\frac{\partial e^*}{\partial \sigma} + \frac{\partial p}{\partial v}\frac{\partial v^*}{\partial \sigma}][U'\{I_s\}\frac{\partial I_s}{\partial r}]$ $+[\frac{\partial p}{\partial e}\frac{\partial e^*}{\partial r} + \frac{\partial p}{\partial v}\frac{\partial v^*}{\partial r}][U'\{I_s\}\frac{\partial I_s}{\partial \sigma} - U'\{I_f\}\frac{\partial I_f}{\partial \sigma}] + p(e,v)[U''\{I_s\}\frac{\partial I_s}{\partial r}\frac{\partial I_s}{\partial \sigma} + U'\{I_s\}\frac{\partial^2 I_s}{\partial \sigma \partial r}] - (\frac{\partial c}{\partial e}\frac{\partial^2 e^*}{\partial \sigma \partial r})$. The sign of the first term, $[\frac{\partial p}{\partial e}\frac{\partial^2 e^*}{\partial \sigma \partial r} + \frac{\partial p}{\partial v}\frac{\partial^2 v^*}{\partial \sigma \partial r}][U\{I_s\} - U\{I_f\}]$, is the same as the signs of $\frac{\partial^2 e^*}{\partial \sigma \partial r}$ and $\frac{\partial^2 v^*}{\partial \sigma \partial r}$ because $\frac{\partial p}{\partial e} > 0$, $\frac{\partial p}{\partial v} > 0$, and $U\{I_s\} > U\{I_f\}$ in an interior equilibrium (from Theorem 1). The second term, $[\frac{\partial p}{\partial e}\frac{\partial e^*}{\partial \sigma} + \frac{\partial p}{\partial v}\frac{\partial v^*}{\partial \sigma}][U'\{I_s\}\frac{\partial I_s}{\partial r}]$ is negative when both $\frac{\partial e^*}{\partial \sigma} > 0$ and $\frac{\partial v^*}{\partial \sigma} > 0$ because $\frac{\partial I_s}{\partial r} = \sigma[\pi'(x'(r)) - x(r) - rx'(r)] < 0$ from Theorem 1. The third term, $[\frac{\partial p}{\partial e}\frac{\partial e^*}{\partial r} + \frac{\partial p}{\partial v}\frac{\partial v^*}{\partial r}][U'\{I_s\}\frac{\partial I_s}{\partial \sigma} - U'\{I_f\}\frac{\partial I_f}{\partial \sigma}]$, is negative if the inventor is risk-neutral (i.e. $U'\{I_s\} = U'\{I_f\}$) or not too risk averse ($U'\{I_f\} - U'\{I_s\}$ small) because $\frac{\partial e^*}{\partial r} < 0$ and $\frac{\partial v^*}{\partial r} < 0$ from Theorem 1 (if royalty revenue is decreasing in the royalty rate, or if $\sigma > \alpha$), and because $\frac{\partial I_s}{\partial \sigma} = \pi(x(r)) - C - rx(r) - F > \frac{\partial I_f}{\partial \sigma} = -C - F$. The fourth term, $p(e,v)[U''\{I_s\}\frac{\partial I_s}{\partial r}\frac{\partial I_s}{\partial \sigma} + U'\{I_s\}\frac{\partial^2 I_s}{\partial \sigma \partial r}]$, is negative if the inventor is risk-neutral ($U''\{I_s\} = 0$) or not too risk-averse (small $U''\{I_s\}$) because $p(e,v) > 0$, $U'\{I_s\} > 0$, and $\frac{\partial^2 I_s}{\partial \sigma \partial r} = \pi'(x'(r)) - x(r) - rx'(r) = -x(r) < 0$ from the envelope theorem. The fifth term, $-(\frac{\partial c}{\partial e}\frac{\partial^2 e^*}{\partial \sigma \partial r})$ is positive if $\frac{\partial^2 e^*}{\partial \sigma \partial r} < 0$ because $\frac{\partial c}{\partial e} > 0$.

Thus, if $\frac{\partial^2 e^*}{\partial\sigma\partial r} < 0$, $\frac{\partial^2 v^*}{\partial\sigma\partial r} < 0$ (or its coefficient $\frac{\partial p}{\partial v}$ is small), and the marginal cost of effort ($\frac{\partial c}{\partial e}$) in the fifth term is small, then overall, $\frac{\partial^2 P_I}{\partial\sigma\partial r}$ is negative. The next task, then, is to sign $\frac{\partial^2 e^*}{\partial\sigma\partial r}$. First, recall that $\frac{\partial e^*}{\partial\sigma} = [\frac{\partial^2 P_I}{\partial e\partial v}\frac{\partial^2 P_M}{\partial v\partial\sigma} - \frac{\partial^2 P_M}{\partial v^2}\frac{\partial^2 P_I}{\partial e\partial\sigma}]/D$ from Theorem 1. Thus, $\frac{\partial^2 e^*}{\partial\sigma\partial r} = [D\{[\frac{\partial^3 P_I}{\partial e\partial v\partial r}\frac{\partial^2 P_M}{\partial v\partial\sigma} + \frac{\partial^2 P_I}{\partial e\partial v}\frac{\partial^3 P_M}{\partial v\partial\sigma\partial r}] - [\frac{\partial^3 P_M}{\partial v^2\partial r}\frac{\partial^2 P_I}{\partial e\partial\sigma} + \frac{\partial^2 P_M}{\partial v^2}\frac{\partial^3 P_I}{\partial e\partial\sigma\partial r}]\} - \frac{\partial D}{\partial r}[\frac{\partial^2 P_I}{\partial e\partial v}\frac{\partial^2 P_M}{\partial v\partial\sigma} - \frac{\partial^2 P_M}{\partial v^2}\frac{\partial^2 P_I}{\partial e\partial\sigma}]]/D^2$. For ease of exposition for this section of the proof, let A be the coefficient on D, and B be the coefficient on $\frac{\partial D}{\partial r}$, thus $\frac{\partial^2 e^*}{\partial\sigma\partial r} = [D(A) - \frac{\partial D}{\partial r}(B)]/D^2$. To sign, first note that $D^2 > 0$ (D is nonzero from the stability assumption in Theorem 1), and recall $D > 0$ from the stability condition. Next, if $\frac{\partial e^*}{\partial\sigma} > 0$, then B is positive (since B is the numerator of $\frac{\partial e^*}{\partial\sigma}$). The sign of $\frac{\partial D}{\partial r} = [\frac{\partial^3 P_I}{\partial e^2\partial r}\frac{\partial^2 P_M}{\partial v^2} + \frac{\partial^2 P_I}{\partial e^2}\frac{\partial^3 P_M}{\partial v^2\partial r}] - [\frac{\partial^2 P_I}{\partial e\partial v}\frac{\partial^3 P_I}{\partial v\partial e\partial r} + \frac{\partial^3 P_I}{\partial e\partial v\partial r}\frac{\partial^2 P_M}{\partial v\partial e}]$ is generally ambiguous; however, we can show that given the second-order conditions, $\frac{\partial D}{\partial r} < 0$. To see this, consider first that the signs of the individual derivatives (if the inventor is not too risk-averse) in $\frac{\partial D}{\partial r}$ are $[(+)(-)+(-)(+)] - [(+)(-)+(-)(+)]$. Thus if each of the two terms in the second bracket can be shown to be smaller in absolute value than corresponding terms in the first bracket, the sign of the first bracket dominates and thus $\frac{\partial D}{\partial r} < 0$.

Comparing terms, $\left|\frac{\partial^3 P_I}{\partial e\partial v\partial r}\right| < \left|\frac{\partial^3 P_I}{\partial e^2\partial r}\right|$ if $\left|\frac{\partial^2 p}{\partial e\partial v}\right| < \left|\frac{\partial^2 p}{\partial e^2}\right|$; $\left|\frac{\partial^2 P_M}{\partial v\partial e}\right| < \left|\frac{\partial^2 P_M}{\partial v^2}\right|$ if $\left|\frac{\partial^2 p}{\partial v\partial e}\right| < \left|\frac{\partial^2 p}{\partial v^2}\right|$; assuming $c''(e)$ is small, $\left|\frac{\partial^2 P_I}{\partial e\partial v}\right| < \left|\frac{\partial^2 P_I}{\partial e^2}\right|$ if $\left|\frac{\partial^2 p}{\partial e\partial v}\right| < \left|\frac{\partial^2 p}{\partial e^2}\right|$; and finally $\left|\frac{\partial^3 P_M}{\partial v\partial e\partial r}\right| < \left|\frac{\partial^3 P_M}{\partial v^2\partial r}\right|$ if $\left|\frac{\partial^2 p}{\partial v\partial e}\right| < \left|\frac{\partial^2 p}{\partial v^2}\right|$, where all inequalities hold because of the second-order conditions. Thus, the four comparisons show that $\frac{\partial D}{\partial r} < 0$ under stability. Similar comparisons reveal that $A < 0$.

If σ and α are relatively small, then $\frac{\partial^3 P_I}{\partial e^2\partial r}$ and $\frac{\partial^3 P_I}{\partial e\partial v\partial r}$(in $\frac{\partial D}{\partial r}$ and A) are small. If sufficiently small, then $D > \left|\frac{\partial D}{\partial r}\right|$ if $\left|\frac{\partial^2 P_M}{\partial v^2}\right| > \frac{\partial^3 P_M}{\partial v^2\partial r}$, which holds if $\pi(x(r)) - rx(r) > x(r)$. In addition, $|A| > B$ if $\pi(x(r)) - rx(r) < 2x(r)$. Thus, $|D(A)| > \left|\frac{\partial D}{\partial r}(B)\right|$ under these conditions and therefore $\frac{\partial^2 e^*}{\partial\sigma\partial r} < 0$. Thus, overall, $\frac{\partial^2 P_I}{\partial\sigma\partial r} < 0$ and $\frac{d\sigma^*}{dr} < 0$ if $\frac{\partial c}{\partial e}$, $\frac{\partial c}{\partial v}$, $\frac{\partial^2 c}{\partial e^2}$, $\frac{\partial^2 c}{\partial v^2}$, σ,and α are sufficiently small and $(x(r) < \pi(x(r)) - rx(r) < 2x(r))$

For the fixed fee effect on ownership shares$\frac{\partial\sigma^*}{\partial F}$, first note that in (17), the sign of $\frac{d\sigma^*}{dF}$ is the same as the sign of $\frac{\partial^2 P_I}{\partial\sigma\partial F}$ when $\frac{\partial^2 P_I}{\partial\sigma^2}$ is strictly negative. Using (14), $\frac{\partial^2 P_I}{\partial\sigma\partial F} = [\frac{\partial p}{\partial e}\frac{\partial^2 e^*}{\partial\sigma\partial F} + \frac{\partial p}{\partial v}\frac{\partial^2 v^*}{\partial\sigma\partial F}][U\{I_s\} - U\{I_f\}] + [\frac{\partial p}{\partial e}\frac{\partial e^*}{\partial\sigma} + \frac{\partial p}{\partial v}\frac{\partial v^*}{\partial\sigma}][U'\{I_s\}\frac{\partial I_s}{\partial F} - U'\{I_f\}\frac{\partial I_f}{\partial F}] + [\frac{\partial p}{\partial e}\frac{\partial e^*}{\partial F} + \frac{\partial p}{\partial v}\frac{\partial v^*}{\partial F}][U\{I_s\}\frac{\partial I_s}{\partial\sigma} - U\{I_f\}\frac{\partial I_f}{\partial\sigma}] + p(e,v)[U''\{I_s\}\frac{\partial I_s}{\partial F}\frac{\partial I_s}{\partial\sigma} + U'\{I_s\}\frac{\partial^2 I_s}{\partial\sigma\partial F}] - (\frac{\partial c}{\partial e}\frac{\partial^2 e^*}{\partial\sigma\partial F})$. The sign of the first term, $[\frac{\partial p}{\partial e}\frac{\partial^2 e^*}{\partial\sigma\partial F} + \frac{\partial p}{\partial v}\frac{\partial^2 v^*}{\partial\sigma\partial F}][U\{I_s\} - U\{I_f\}]$, is the same as the signs of $\frac{\partial^2 e^*}{\partial\sigma\partial F}$ and $\frac{\partial^2 v^*}{\partial\sigma\partial F}$ because $\frac{\partial p}{\partial e} > 0$, $\frac{\partial p}{\partial v} > 0$, and $U\{I_s\} > U\{I_f\}$ in an interior equilibrium (from Theorem 1). The second term, $[\frac{\partial p}{\partial e}\frac{\partial e^*}{\partial\sigma} + \frac{\partial p}{\partial v}\frac{\partial v^*}{\partial\sigma}][U'\{I_s\}\frac{\partial I_s}{\partial F} - U'\{I_f\}\frac{\partial I_f}{\partial F}]$ is zero because $\frac{\partial I_s}{\partial F} = \frac{\partial I_f}{\partial F}$ and $U'\{I_s\} = U'\{I_f\}$ under risk-neutrality. The third term, $[\frac{\partial p}{\partial e}\frac{\partial e^*}{\partial F} + \frac{\partial p}{\partial v}\frac{\partial v^*}{\partial F}][U'\{I_s\}\frac{\partial I_s}{\partial\sigma} - U'\{I_f\}\frac{\partial I_f}{\partial\sigma}]$, is zero under risk-neutrality from Theorem 1 ($\frac{\partial e^*}{\partial F} = 0$ and $\frac{\partial v^*}{\partial F} = 0$). The fourth term, $p(e,v)[U''\{I_s\}\frac{\partial I_s}{\partial F}\frac{\partial I_s}{\partial \sigma} + U'\{I_s\}\frac{\partial^2 I_s}{\partial \sigma \partial F}]$, is negative under risk neutrality because $U'' = 0$ and $\frac{\partial^2 I_s}{\partial \sigma \partial F} = -1$. The fifth term, $-(\frac{\partial c}{\partial e}\frac{\partial^2 e^*}{\partial \sigma \partial F})$ is positive if $\frac{\partial^2 e^*}{\partial \sigma \partial F} < 0$ because $\frac{\partial c}{\partial e} > 0$. To sign $\frac{\partial^2 e^*}{\partial \sigma \partial F}$, recall that $\frac{\partial e^*}{\partial \sigma} = [\frac{\partial^2 P_I}{\partial e \partial v}\frac{\partial^2 P_M}{\partial v \partial \sigma} - \frac{\partial^2 P_M}{\partial v^2}\frac{\partial^2 P_I}{\partial e \partial \sigma}]/D$ from Theorem 1. Thus, $\frac{\partial^2 e^*}{\partial \sigma \partial F} = [D\{[\frac{\partial^3 P_I}{\partial e \partial v \partial F}\frac{\partial^2 P_M}{\partial v \partial \sigma} + \frac{\partial^2 P_I}{\partial e \partial v}\frac{\partial^3 P_M}{\partial v \partial \sigma \partial F}] - [\frac{\partial^3 P_M}{\partial v^2 \partial F}\frac{\partial^2 P_I}{\partial e \partial \sigma} + \frac{\partial^2 P_M}{\partial v^2}\frac{\partial^3 P_I}{\partial e \partial \sigma \partial F}]\} - \frac{\partial D}{\partial F}[\frac{\partial^2 P_I}{\partial e \partial v}\frac{\partial^2 P_M}{\partial v \partial \sigma} - \frac{\partial^2 P_M}{\partial v^2}\frac{\partial^2 P_I}{\partial e \partial \sigma}]]/D^2$. Under risk-neutrality, $\frac{\partial^3 P_I}{\partial e \partial v \partial F} = \frac{\partial^3 P_M}{\partial v \partial \sigma \partial F} = \frac{\partial^3 P_M}{\partial v^2 \partial F} = \frac{\partial^3 P_I}{\partial e \partial \sigma \partial F} = \frac{\partial D}{\partial F} = 0$, thus $\frac{\partial^2 e^*}{\partial \sigma \partial F} = 0$. Note also that $\frac{\partial^2 v^*}{\partial \sigma \partial F} = [D\{[\frac{\partial^3 P_M}{\partial v \partial e \partial F}\frac{\partial^2 P_I}{\partial e \partial \sigma} + \frac{\partial^2 P_M}{\partial v \partial e}\frac{\partial^3 P_I}{\partial e \partial \sigma \partial F}] - [\frac{\partial^3 P_I}{\partial e^2 \partial F}\frac{\partial^2 P_M}{\partial v \partial \sigma} + \frac{\partial^2 P_I}{\partial e^2}\frac{\partial^3 P_M}{\partial v \partial \sigma \partial F}]\} - \frac{\partial D}{\partial F}[\frac{\partial^2 P_M}{\partial v \partial e}\frac{\partial^2 P_I}{\partial e \partial \sigma} - \frac{\partial^2 P_I}{\partial e^2}\frac{\partial^2 P_M}{\partial v \partial \sigma}]]/D^2$. Under risk-neutrality, $\frac{\partial^3 P_M}{\partial v \partial e \partial F} = \frac{\partial^3 P_I}{\partial e \partial \sigma \partial F} = \frac{\partial^3 P_I}{\partial e^2 \partial F} = \frac{\partial^3 P_M}{\partial v \partial \sigma \partial F} = 0$, thus $\frac{\partial^2 v^*}{\partial \sigma \partial F} = 0$. Therefore, under risk-neutrality, $\frac{\partial \sigma^*}{\partial F} = -p(e,v)[U'\{I_s\}] < 0$. ∎

Proof. Theorem 4

From (23), the second and fourth terms in the braces, $\frac{\partial p}{\partial e}\frac{\partial e^*}{\partial \sigma}\frac{\partial \sigma^*}{\partial r}$ and $\frac{\partial p}{\partial e}\frac{\partial v^*}{\partial \sigma}\frac{\partial \sigma^*}{\partial r}$, are zero in the case of an established firm license ($\frac{\partial \sigma^*}{\partial r} = 0$) and negative in the case of a start-up license ($\frac{\partial \sigma^*}{\partial r} < 0$, $\frac{\partial p}{\partial e} > 0$, $\frac{\partial p}{\partial v} > 0$, $\frac{\partial e^*}{\partial \sigma} > 0$, and $\frac{\partial v^*}{\partial \sigma} > 0$), thus evaluated at the optimum royalty rate for an established firm, $\frac{\partial T(e^*,v^*)}{\partial r} < 0$ for a start-up firm.

If the inventor's participation constraint is binding ($\lambda_1 > 0$), then the lower royalty rate relaxes the constraint if $\partial^2 L/\partial \lambda_1 \partial r = \frac{\partial P_I^*}{\partial r} < 0$. Using (20), $\frac{\partial P_I^*}{\partial r} = (\frac{\partial p}{\partial e}\frac{\partial e^*}{\partial r} + \frac{\partial p}{\partial e}\frac{\partial e^*}{\partial \sigma}\frac{\partial \sigma^*}{\partial r} + \frac{\partial p}{\partial v}\frac{\partial v^*}{\partial r} + \frac{\partial p}{\partial e}\frac{\partial v^*}{\partial \sigma}\frac{\partial \sigma^*}{\partial r})[U(I_s) - U(I_f)] + p(e^*(\cdot), v^*(\cdot))[U'(I_s)\frac{\partial I_s}{\partial r} - U'(I_f)\frac{\partial I_f}{\partial r}] + U'(I_f)\frac{\partial I_f}{\partial r} - c'(e)(\frac{\partial e^*}{\partial r} + \frac{\partial e^*}{\partial \sigma}\frac{\partial \sigma^*}{\partial r})$, which is negative if $c'(e)$ and $U'(I_f)\frac{\partial I_f}{\partial r}$ are small. Thus, a lower royalty rate will increase inventor returns if the increased cost of higher effort ($c'(e)(\frac{\partial e^*}{\partial r} + \frac{\partial e^*}{\partial \sigma}\frac{\partial \sigma^*}{\partial r})$) and greater loss under failure ($U'(I_f)\frac{\partial I_f}{\partial r}$) is more than offset by the higher total effort effect on the probability of success (first term) and the higher expected gain to the firm's returns from success (second term).

If the start-up firm's participation constraint is binding ($\lambda_2 > 0$), then the constraint is relaxed if $\partial^2 L/\partial \lambda_2 \partial r = \frac{\partial P_M^*}{\partial r} < 0$. Using (21), $\frac{\partial P_M^*}{\partial r} = (1-\sigma)(\frac{\partial p}{\partial e}\frac{\partial e^*}{\partial r} + \frac{\partial p}{\partial e}\frac{\partial e^*}{\partial \sigma}\frac{\partial \sigma^*}{\partial r} + \frac{\partial p}{\partial v}\frac{\partial v^*}{\partial r} + \frac{\partial p}{\partial e}\frac{\partial v^*}{\partial \sigma}\frac{\partial \sigma^*}{\partial r})\Pi - \frac{\partial \sigma^*}{\partial r}p(e^*(\cdot), v^*(\cdot))\Pi + (1-\sigma)p(e^*(\cdot), v^*(\cdot))[\pi'(x'(r)) - x(r) - rx'(r)]$. The first and third terms are negative and the second term is positive, thus a lower royalty rate will increase firm payoff if the reduced ownership effect (second term) of a lower royalty rate is small relative to the increased effort effect (first term) and the increased firm profit effect (third term).

For the fixed fee effect, using (24), the second and fourth terms in the braces, $\frac{\partial p}{\partial e}\frac{\partial e^*}{\partial \sigma}\frac{\partial \sigma^*}{\partial F}$ and $\frac{\partial p}{\partial e}\frac{\partial v^*}{\partial \sigma}\frac{\partial \sigma^*}{\partial F}$, are zero in the case of an established firm license ($\frac{\partial \sigma^*}{\partial r} = 0$) and negative in the case of a start-up license ($\frac{\partial \sigma^*}{\partial F} < 0$, $\frac{\partial p}{\partial e} > 0$, $\frac{\partial p}{\partial v} > 0$, $\frac{\partial e^*}{\partial \sigma} > 0$, and $\frac{\partial v^*}{\partial \sigma} > 0$), thus evaluated at the optimum royalty rate for an established firm, $\frac{\partial T(e^*,v^*)}{\partial F} < 0$ for a start-up firm. If the inventor's participation constraint is binding ($\lambda_1 > 0$), then the lower royalty rate relaxes the constraint if $\partial^2 L/\partial\lambda_1\partial F = \frac{\partial P_I^*}{\partial F} < 0$. Using (20), $\frac{\partial P_I^*}{\partial F} = (\frac{\partial p}{\partial e}\frac{\partial e^*}{\partial F} + \frac{\partial p}{\partial e}\frac{\partial e^*}{\partial \sigma}\frac{\partial \sigma^*}{\partial F} + \frac{\partial p}{\partial v}\frac{\partial v^*}{\partial F} + \frac{\partial p}{\partial e}\frac{\partial v^*}{\partial \sigma}\frac{\partial \sigma^*}{\partial F})[U(I_s) - U(I_f)] + p(e^*(\cdot), v^*(\cdot))[U'(I_s)\frac{\partial I_s}{\partial F} - U'(I_f)\frac{\partial I_f}{\partial F}] + U'(I_f)\frac{\partial I_f}{\partial F} - c'(e)(\frac{\partial e^*}{\partial F} + \frac{\partial e^*}{\partial \sigma}\frac{\partial \sigma^*}{\partial F})$. From Theorem 1, $\frac{\partial e^*}{\partial F} = 0$ and $\frac{\partial v^*}{\partial F} = 0$, so the first term is negative for a start-up and zero for an established firm. The second term is ambiguous. The third term is positive for a start-up and zero for an established firm. The fourth term is positive. Thus, if any possible decreased expected utility from firm returns plus increased effort from a lower royalty rate are offset by the higher effort effect on success probability, then inventor return increases and the constraint is relaxed.

If the start-up firm's participation constraint is binding ($\lambda_2 > 0$), then the constraint is relaxed if $\partial^2 L/\partial\lambda_2\partial F = \frac{\partial P_M^*}{\partial F} < 0$. Using (21), $\frac{\partial P_M^*}{\partial F} = (1-\sigma)(\frac{\partial p}{\partial e}\frac{\partial e^*}{\partial F} + \frac{\partial p}{\partial e}\frac{\partial e^*}{\partial \sigma}\frac{\partial \sigma^*}{\partial F} + \frac{\partial p}{\partial v}\frac{\partial v^*}{\partial F} + \frac{\partial p}{\partial v}\frac{\partial v^*}{\partial \sigma}\frac{\partial \sigma^*}{\partial F})\Pi - \frac{\partial \sigma^*}{\partial F}p(e^*(\cdot), v^*(\cdot))\Pi - (1-\sigma)$. The first and third terms are negative and the second term is positive, thus a lower fixed fee will increase firm payoff if the reduced ownership effect (second term) of a lower fixed fee is small relative to the increased effort effect (first term) and direct effect of lower firm profits (third term). ■

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Proof. Theorem 5.

A decrease in s relaxes the participation constraint of the inventor ($\frac{\partial P_I^*}{\partial s} < 0$), which induces the TTO to reduce the royalty rate (from Theorem 3) and raises T_ρ relative to T_μ (from Theorem 4). From (25), an increase in w decreases T_μ relative to T_ρ. If $\frac{\partial \sigma^*}{\partial r} < 0$, then a decrease in the royalty rate increases T_ρ relative to T_μ (from (23) and Theorem 4). ■

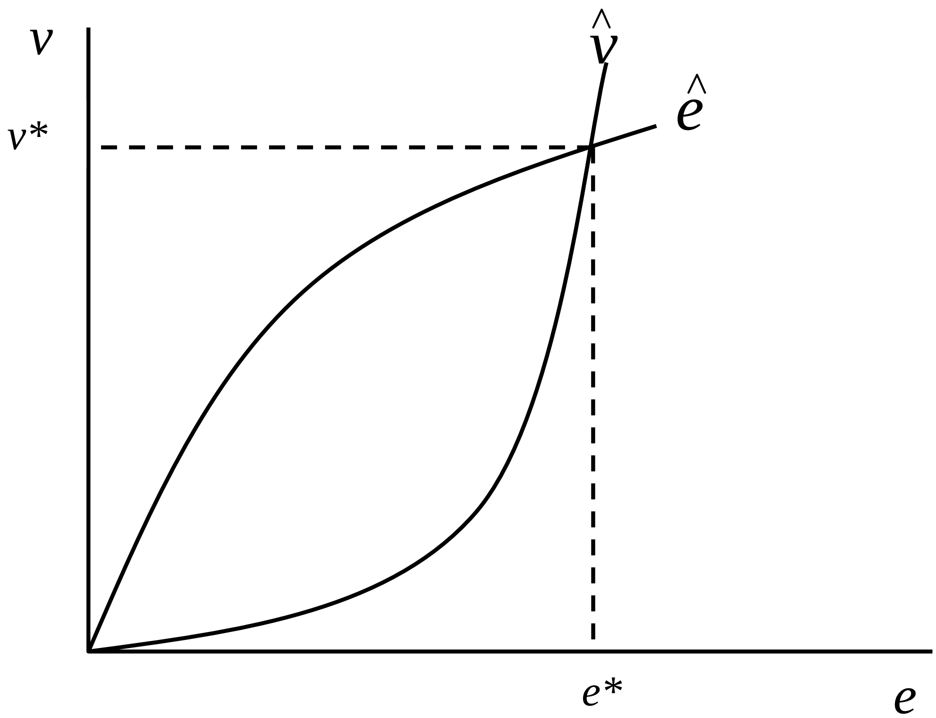

Figure 1

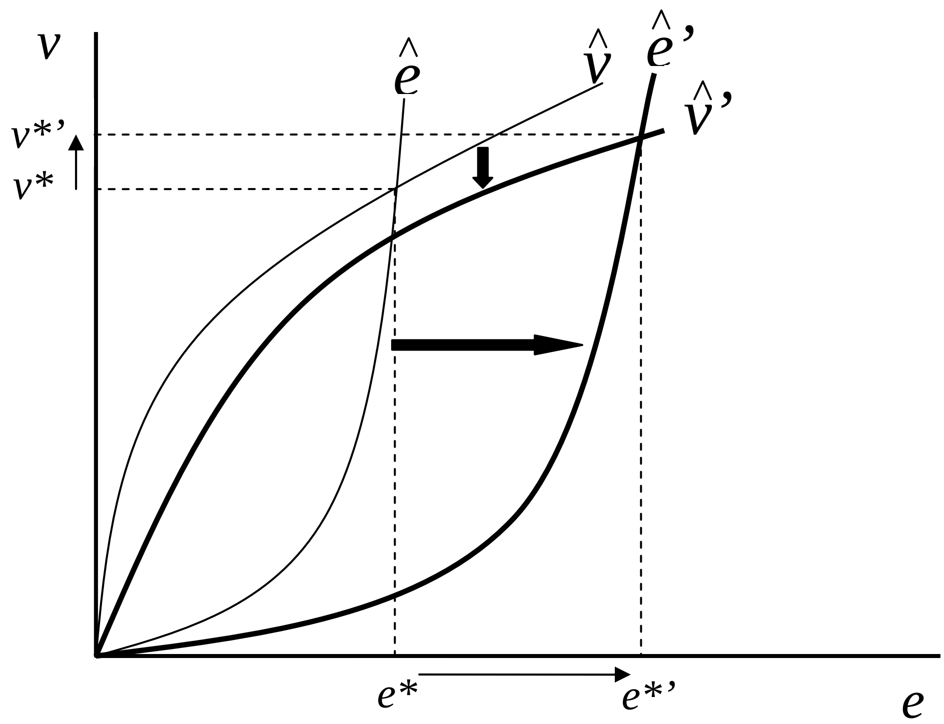

Figure 2