Proofs and Prototypes for Sale: The Licensing of University Inventions

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Proponents of the Bayh-Dole Act argue that industrial use of federally funded research would be reduced without university patent licensing. Our survey of U.S. universities supports this view, emphasizing the embryonic state of most technologies licensed and the need for inventor cooperation in commercialization. Thus, for most university inventions, there is a moral-hazard problem with inventor effort. For such inventions, development does not occur unless the inventor's income is tied to the licensee's output by payments such as royalties or equity. Sponsored research from the licensee cannot by itself solve this problem. (*JEL* O31, O34, O38)

University licensing has increased dramatically since the passage of the Bayh-Dole Act in 1980, which gave universities the right to retain title to and license inventions resulting from federally sponsored research. The *Association of University Technology Managers Survey Fiscal Year 1996* (AUTM, 1997) reports that licenses executed increased 75 percent between 1991 and 1996, with 13,087 executed over the entire period. Such statistics notwithstanding, the Act has been subject to increasing congressional review and debate. At issue is whether the commercial application and diffusion of inventions from federally funded research critically depends upon allowing universities to retain title to and license them. This paper directly addresses this issue by providing survey evidence of the licensing practices of 62 U.S. universities, and analyzing several related theoretical models of licensing consistent with the types of licenses executed.

University licensing agreements, with the exception of those for software and reagent materials, invariably include both fixed fees and royalties. Many license agreements also include sponsored research clauses, and increasingly, equity. The theoretical literature on licensing has largely abstracted from institutional features of this sort and focused on inventors who maximize profit from the sale of licenses. In a university setting, profit maximization is rarely the objective. Moreover, recent legal suits suggest that there are differences in the objectives of inventors, technology managers, and university administrators.[1] Indeed, technology managers responding to our survey viewed themselves as balancing the interests of university administrators with those of inventors, who often prefer sponsored research to the objectives of administrators.

Perhaps the most striking result of the survey is that when they are licensed, most university inventions are little more than a "proof of concept." No one knows their commercial potential because

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[1] In two highly publicized lawsuits, University of California System researchers sued the University, claiming the University ignored their financial interests when it negotiated license agreements (Jonathan N. Axelrod, 1996).

they are in such an early stage of development. Indeed, they are so embryonic that additional effort in development by the inventor is required for a reasonable chance of commercial success. To capture this fact, our theoretical analysis focuses on inventions for which the probability of success is zero at the time of licensing, but increases with additional inventor effort. This assumption is sufficient to show that optimal license contracts cannot rely solely on lump-sum payments, such as fixed fees or funds for sponsored research, but also must involve some sort of output-based payments, such as royalties. The intuition is simple. A lump-sum payment provides no incentive for the inventor to expend further effort in development. Because inventor effort increases the probability of commercial success, royalties solve this moral-hazard problem by linking the inventor's license income to additional effort. Other output-based payments, such as equity, solve the moral-hazard problem without the inefficiency inherent in royalties. It is important to note that assuming the probability of success is zero in the absence of inventor effort is not necessary. These results hold if this probability is positive but small enough that no firm would attempt to commercialize the invention without sufficient additional inventor effort.

Our analysis contributes to the debate over the Bayh-Dole Act, which has been the focus of a recent Government Accounting Office review (GAO, 1998) and an April 1999 U.S. Senate Hearing on Federal R&D (*Congressional Record,* 1999). The Act allows universities to retain title to federally funded inventions, in return for which they must file for patents and collaborate with businesses to promote commercial application of the inventions they elect to own. Prior to Bayh-Dole, the primary method for disseminating federally funded research was academic publication (David C. Mowery et al., 2001). Evidence based on publication citations shows that the lag between publication of scholarly research and its application by industry averages 20 years (James D. Adams, 1990).[2] Proponents of Bayh-Dole therefore argue that university licensing accelerates the timing of commercialization and that, with the rapid growth in university technology transfer offices and patenting, businesses have better information on university inventions. The opposing view is that much of the increase in patenting involves low-quality patents and that exclusive licensing is not required for commercialization of high-quality patents. Nonetheless, there is empirical support for the view that Bayh-Dole has increased industrial application of university inventions (Rebecca Henderson et al., 1998). Our results add a new dimension to the debate by highlighting the fact that many inventions are so embryonic that they might remain in the lab without license agreements designed to induce collaboration between inventors and licensees.[3]

We also bring an institutional dimension to the theoretical literature on patent licensing by providing a new explanation for the use of royalties. With few exceptions, the main result of this literature is that inventor profit is maximized when licensees pay a fixed fee determined by an auction rather than royalties (see Morton I. Kamien [1992] for a survey).[4] The reason for this is simply that a fixed fee does not distort the licensee's output decision by increasing the marginal cost of production. However, fixed fees alone are not optimal for licensing university inventions because of the need to induce additional inventor effort.

The theoretical work closest to ours is that of Philippe Aghion and Jean Tirole (1994a, b), who examine the organization of R&D in an incomplete contract framework.[5] However,

[2] In a recent survey of firms that use academic research in their product and process development, Edwin Mansfield (1995) found that the average lag between research findings and commercial application was seven years. Unfortunately, it is not clear from his data whether research results were obtained by license, consulting arrangements, or other means such as publication.

[3] In fact, commercialization by an exclusive licensee can become a problem if the inventor and licensee do not see eye to eye on how best to proceed with development. This seems to have been the case with Columbia University's invention aimed to treat glaucoma. This example was provided by Richard R. Nelson, who is developing case studies of Columbia inventions.

[4] See Nancy T. Gallini and Brian D. Wright (1990), Alan W. Beggs (1992), Jensen (1992a, b), and X. Henry Wang (1998) for exceptions.

[5] Joshua Lerner and Robert Merges (1997) test Aghion and Tirole's hypotheses for biotechnology alliances, looking at assignment of control rights and stage of the projects when alliances are signed.

their work focuses on efficiency aspects of whether an invention is owned by the research unit, final customer, or some combination. They derive conditions under which ownership is irrelevant for efficiency. One is that either the research unit or the customer can develop the invention independently. Applied to university R&D, this would mean that it does not matter whether universities or licensees own the invention. Given the dramatic response of universities to the Bayh-Dole Act, irrelevance of ownership seems unlikely. Moreover, our survey results make it clear that most university inventions could not be developed independently by either the inventor or the firm.

This paper also contributes to the empirical literature on the industrial impact of university research. With few exceptions, this literature has focused on spillovers from university research via citations to journal articles or to patents.[6] Lynne G. Zucker and Michael R. Darby (1996) point out that the commercialization of scientific breakthroughs in biotechnology depends not only on the publications of "star" scientists, but also their active involvement.[7] Our survey shows this collaboration between universities and businesses extends well beyond biotechnology.

In Section I, we focus on the survey results, and in subsequent sections, we present several closely related models of university licensing. The models in Section II highlight the role of inventor effort in commercialization. In Section III, we examine cases in which development requires both inventor effort and firm expenditure on sponsored research. We show that a contract with sponsored research does not solve the inventor's moral-hazard problem unless it also includes output-based payments. Section IV concludes the paper. We discuss survey design in Appendix A, and we sketch the proofs of all theorems in Appendix B.

[6] See Nelson (1982), Adam B. Jaffe (1989), Jaffe et al. (1993), and Henderson et al. (1998).

[7] Zucker et al. (1994) and Zucker et al. (1998) use this collaboration to explain the location of biotechnology firms.

I. University Technology Transfer

To understand the nature of university inventions and the types of contracts used to license them, we conducted a survey of 62 U.S. research universities.[8] Respondents were either directors or licensing officers of the technology transfer office (TTO) of each university. These offices are responsible for soliciting reports (disclosures) on faculty inventions, assessing commercial potential of inventions, filing patent applications, finding potential licensees, and executing and monitoring license agreements. Respondents were asked to complete a questionnaire concerning their licensing activities for fiscal years 1991–1995. As reported below, questions focused on the characteristics of inventions available for license, the objectives of the TTO, as well as license characteristics.[9]

A. *Invention Characteristics*

Table 1 summarizes responses on the characteristics of inventions disclosed and licensed over the sample period. Most inventions came from the schools of science, engineering, medicine, and nursing. The research leading to 63 percent of the inventions was federally funded, 17 percent was sponsored by industry, and 20 percent was unsponsored. Patentable inventions are usually considered university property rather than property of either the faculty-inventor or the sponsor. This follows from the Bayh-Dole Act in the case of federally funded inventions, and it is university policy regardless of sponsorship for all but one university in the sample.[10]

Inventions are highly variable in terms of commercial potential. Less than half of the inventions disclosed were licensed, with 31 per-

[8] These universities accounted for 67 percent of the invention disclosures, 70 percent of the licenses, and 68 percent of the revenue received by AUTM members during this period.

[9] For other issues addressed in the survey, see Jerry G. Thursby and Sukanya Kemp (2001), Thursby and Thursby (2001), and Thursby et al. (2001).

[10] Some universities grant ownership to corporate sponsors who cover all direct and indirect research costs. For copyrightable materials, 48 percent of the respondents reported inventors retain title to inventions.

TABLE 1—INVENTION CHARACTERISTICS

Invention disclosures (1991–1995)	Weighted mean[a] (Percent)
1. Filed by faculty in schools of	
Science	19
Engineering	25
Medicine and nursing	44
Agriculture	5
Other	7
2. Resulting from	
Federal-sponsored research	63
Corporate-sponsored research	17
3. Subject to	
Exclusive license	21
Exclusive license for field of use	10
Nonexclusive license	10
Not currently licensed	61
4. Revenue from top five inventions	78
5. Stage of development for inventions which were licensed[b]	
Proof of concept but no prototype	48
Prototype available but only lab scale	29
Some animal data available	25
Some clinical data available	5
Manufacturing feasibility known	8
Inventor cooperation required	71
Ready for practical or commercial use	12

[a] Weighted mean = $\Sigma\, x_i w_i / \Sigma\, w_i$, where x_i is the percentage for each university, and w_i is university i's weight. The weight is the number of invention disclosures for 1, 2, and 3, the gross revenue for 4, and the number of license agreements for 5. Data for disclosures, license agreements and revenue are from the *AUTM Survey* (1997).
[b] Stage of development at the time the license was executed. Percentages need not sum to 100.
Source: Authors' calculation.

cent either licensed exclusively or exclusively for field of use. In terms of earnings, the top five inventions licensed by each university accounted for 78 percent of gross license revenue.[11]

Our most striking result concerns the embryonic nature of the inventions that are licensed.[12] Only 12 percent were ready for commercial use at the time of license, and manufacturing feasibility was known only for 8 percent.[13] Over 75 percent of the inventions licensed were no more than a proof of concept (48 percent with no prototype available) or lab scale prototype (29 percent) at the time of license! Thus, an overwhelming majority of university inventions require further development once they are licensed. Moreover, TTO managers believe efforts by licensee-firms alone to develop embryonic inventions are unlikely to succeed. For 71 percent of the inventions licensed, respondents claim that successful commercialization requires cooperation by the inventor and the licensee in further development.

B. *Licensing Objectives*

Respondents were asked about their own objectives and their perceptions of faculty and university administration objectives. While TTO managers execute the licenses, they report to the university administration and rely on faculty to disclose inventions with commercial potential. We were therefore not surprised to find that managers view themselves as balancing faculty and administration objectives. Managers in our pretest indicated that convincing faculty to disclose inventions is a major challenge, and a number of survey respondents stated that balancing the objectives of faculty and administrators is problematic (Thursby et al., 2001).

We asked managers about the importance of five outcomes of their work: license revenue, license agreements executed, inventions commercialized, sponsored research, and patents awarded.[14] We asked if they considered each outcome extremely important (EI), moderately important (MI), not very important (NI), or not applicable (NA), as well as how important they thought each outcome was to their administration and the faculty they work with. The stacked bar charts in Figure 1 show the proportions of EI and MI responses.

[11] This is similar to results in Frederick M. Scherer (1996) for Harvard inventions and Dietmar Harhoff et al. (1997) for German patents.

[12] Even the most lucrative university patents tend to be quite embryonic when licensed. Neils Reimers (1987) notes the importance of the Cohen-Boyer patents was clear at the beginning, but commercial application was viewed as decades away.

[13] The majority of inventions ready for commercial application are reagent materials or software. In many instances, these were licensed for a fixed fee.

[14] Our test group indicated that these outcomes are major criteria used by technology transfer offices to measure their success.

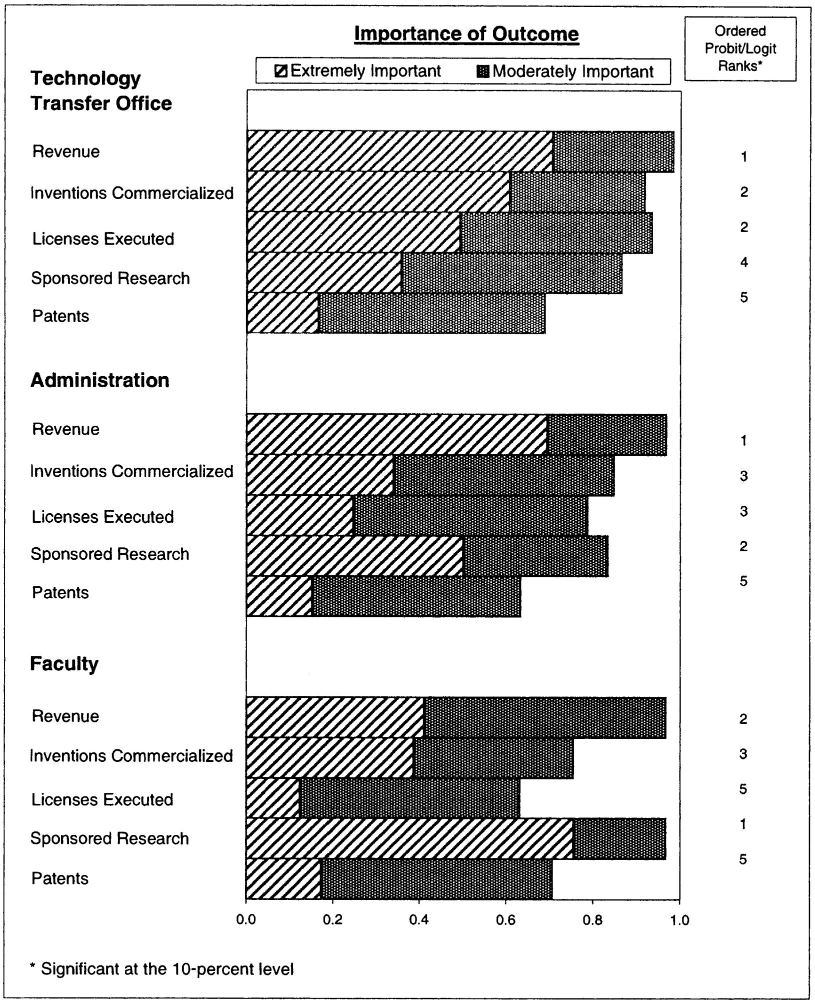

FIGURE 1. OUTCOMES OF TECHNOLOGY TRANSFER

None of the respondents view revenue as their sole motivation for licensing inventions.[15] The outcome considered least important is patents awarded. This may reflect the fact that patents are an intermediate input to licensing. Many managers said that for financial reasons their policy is to apply for a patent on an invention only after they have identified a potential licensee.[16] Finally, there are clear differences among the perceived objectives of the technology transfer office (TTO), administration (ADM), and faculty (FAC).

To examine the ranks accorded different outcomes by the TTO, ADM, and FAC, we considered both ordered logit and probit models with dependent variables equal to the manager's

[15] Few respondents rate any outcomes as unimportant (NI or NA). This could not have occurred had we asked for a ranking of outcomes (or allowed at most one EI choice, one MI choice, etc.), but we did not want to preclude the possibility that all of the outcomes might be elements of a manager's objective function.

[16] See Richard C. Levin et al. (1987) and Wesley Cohen et al. (1997) for similar results (for other reasons) in industry surveys. See Thursby and Thursby (2001) for a model of university patent licensing in which patents are intermediate inputs.

response for an outcome (EI, MI, or NI) and independent variables which are dummies indicating the particular question (outcome). At a 10-percent significance level, both approaches give the same rankings (which include a number of tied ranks). These ranks, along with ties, are on the right in Figure 1.[17]

Technology managers and university administrators (as perceived by TTO managers) consider license revenue more important than any other outcome. Almost as important to the TTO, however, are inventions commercialized and numbers of licenses executed. This is consistent with managers' statements identifying their job as implementing the Bayh-Dole Act. Sponsored research ranks only ahead of patents in importance to TTO managers. On the other hand, managers believe the faculty consider sponsored research more important than any other objective, and they perceive little faculty interest in patents or the execution of license agreements, per se.

Using Kendall's τ, Cohen's κ, and McNemar's Test, we tested for agreement of TTO and FAC (and of TTO and ADM) responses for each of the five outcomes. According to all three tests, TTO managers report their objectives as more closely aligned with the administration than the faculty. TTO and ADM agreement is accepted for each outcome, while TTO and FAC agreement is accepted only for inventions commercialized and sponsored research.

C. *License Characteristics*

We asked a variety of questions about license procedures. We were interested in whether the process should be modeled as an auction. Only two managers cited inventions that had been licensed in this manner. Indeed, most questioned the merits of auctioning university inventions, emphasizing that it is often difficult to find companies interested in early-stage inventions. As shown in Table 2, only 22 percent of the licenses executed had multiple bidders.

[17] We also ranked outcomes by a dual scaling procedure which allows us to estimate the scale assigned to EI, MI, NI, and NA. This procedure gives the same results as our logit and probit estimates.

TABLE 2—LICENSE CHARACTERISTICS

	Weighted mean[a] (Percent)
1. Frequency of more than one company	
Signing a confidentiality agreement	63
Bidding for a license	22
2. Percentage of revenue by payment type	
License issue or up-front fees	7
Running royalties[b]	75
Annual or minimum royalty fees	6
Progress or milestone payments	3
Patent fee reimbursement	7
Equity	3
Other	1
3. Percentage of licenses which include	
License issue or up-front fee	84
Running royalties	84
Annual or minimum royalty fees	78
Progress or milestone payments	58
Patent reimbursement	78
Equity	23
4. Percentage of licenses including equity plus	
License issue or up-front fee	67
Running royalty	79
Other	51
5. Percentage of licenses including sponsored research	33
6. Patent issued at time of license[c]	28
7. (Net revenue) distribution[d]	
Inventor[e]	40
University	35
Department, school or TTO	25

[a] Gross revenue is the weight for 2 and 8, and the number of licenses is the weight for the others.
[b] Running royalties is the common TTO term for output-based fees.
[c] Or copyright registered.
[d] Patentable inventions only. The distribution of revenue from copyrightable inventions is negotiable for 41 percent of the universities surveyed.
[e] For 15 percent of the universities surveyed, the inventors' share of net revenue is ⅓; with ⅓ to the university and ⅓ to other university units. Also, 24 percent of the surveyed universities have sliding scales.
Source: Authors' calculations.

Table 2 also gives information on the types of payments included in licenses. Most licenses include a combination of payment types. Fixed fees (license-issue or annual) and royalties appear in roughly 80 percent of the license agreements, with fees accounting for 13 percent of revenue received and royalties accounting for

75 percent.[18] Note that milestone payments and patent reimbursement are common. While not a large fraction, equity is included in 23 percent of the license agreements. Indeed, the most recent *AUTM Survey* reported that the use of equity in licenses has increased substantially in the last five years. The managers we interviewed indicated that licenses with equity tend to be for enabling technologies to start-up companies. Agreements that include equity also tend to include fees and royalties. Finally, roughly a third of the licenses covered by the survey include sponsored research.[19]

II. University Licensing with Inventor Involvement

This section presents a theoretical analysis of university licensing. In contrast to the usual approach of characterizing optimal incentive contracts, our objective is to predict and evaluate the types of licenses executed by research universities in the United States. Key features of the analysis are the nature of the inventions to be licensed and the objectives of the managers who execute licenses. We follow the survey results in assuming that the invention is so embryonic that at the time the license is executed no one knows if it will lead to a commercially successful product or process. Although the licensee must eventually commit resources to attempt to commercialize the invention, further development by the inventor is essential early on if it is to succeed.

We assume that the invention is owned by the university and the TTO is responsible for executing the license contract. As noted, this is the case for virtually all patentable university inventions, either because of Bayh-Dole or university policy. Faculty are assumed to disclose such inventions to the TTO, at which point the TTO evaluates the invention and searches for a licensee.[20] We model the TTO's objectives as balancing those of the administration and the inventor. This follows our survey evidence, but it is also natural since license revenue from patentable inventions is split between the university and the inventor. On average, inventors in our sample are entitled to 40 percent of revenue, with the remainder allocated to the inventor's school or department, or the TTO or some other unit within the university.

A. *Licensing by Royalties*

Given our survey results, constructing a model of university licensing involves using elements of the literatures on optimal patent licensing, principal-agent problems, and incomplete contracting. We consider a situation in which a faculty-inventor has already disclosed an invention, and the TTO has determined that a given firm is a potential licensee. The invention is either a new product or process whose profitability is uncertain; in particular, neither the inventor nor the TTO nor the firm knows whether the invention will be a commercial success.

The problem is modeled as a game that unfolds over time with the following sequence of actions. The TTO first decides either to shelve the invention, which ends the game, or offer a license contract to the firm. If a contract is offered, then the firm decides either to reject the contract, which ends the game, or accept it. If it accepts, it pays a fixed license fee, and a period of further development follows in which the inventor may expend effort to improve the probability of success. The outcome of this development is an updated probability of success, observed at the end of this period. The firm then decides either to terminate the project, which ends the game, or expend the resources necessary to attempt to commercialize the invention, after which both the TTO and the firm learn whether the invention is a success or not. If it fails, the game ends. If it succeeds, the firm produces and pays royalties.

In the development period, the inventor may expend further effort to improve the chance of success. We assume that e, the "effort cost" of the inventor I, is not contractible, but instead is chosen at the beginning of the development period (after the licensing agreement has been executed). Thus, the inventor is subject to moral hazard in that her effort cannot be effectively

[18] Richard E. Caves et al. (1983) and Ines Macho-Stadler et al. (1996) give similar results for business licenses.

[19] For a number of universities in the sample, the technology transfer office is not responsible for obtaining sponsored research.

[20] In the survey, 58 percent reported inventor cooperation useful in the search for potential licensees.

monitored and/or enforced. This assumption accords well with statements made by the technology managers we interviewed, who overwhelmingly viewed their own actions (and, in fact, the types of contracts they execute) as important for ensuring further development on inventions.[21] The license contract must therefore specify payoffs in a way that induces effort from the inventor. In this section, we confine our attention to licenses that specify a royalty rate (fee per unit of output) and a fixed fee paid by the firm to the university. We denote the royalty rate by r and the fixed fee by m. Given a license characterized by (r, m), the equilibrium level of effort chosen in the development stage is then written as $e^*(r, m)$.

Given any level of inventor effort e, let $p(e)$ be the probability that the invention is a commercial success. In our assumptions on $p(e)$, we are thinking of the 71 percent of university inventions that are so embryonic that commercial success requires further development by the inventor, but for which no amount of inventor effort can guarantee success. Thus, we assume $p(0) = 0$ and $p(e) \in [0, 1)$ for all $e \geq 0$. We also assume $p(e)$ is increasing and concave.

Now suppose additional development, characterized by $e > 0$, has taken place and the invention is a success. Then the firm chooses output to maximize its profit (net of any license fees). In general, as long as production occurs and marginal revenue cuts marginal cost from above, profit-maximizing output is a decreasing function of the royalty rate, but does not depend on the fixed fee.[22] The reason is that the firm's marginal cost of production depends on the royalty rate, but not the fixed fee. Thus, we denote profit-maximizing output $x(r)$. We assume this output is positive if the royalty rate is 0, and decreasing in the royalty rate when it is positive, $x(0) > 0$ and $x'(r) < 0$ for $r > 0$. We further assume that royalty revenue $rx(r)$ is strictly concave in the royalty rate, and takes a unique maximum at some positive but finite value. 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).

Next let $\Pi(x)$ be the profit (gross of any license fees) from producing x units with a successful invention, and let $E > 0$ be the lump-sum cost of attempting to commercialize the invention. Depending on whether the invention is a new product or process, E can be interpreted as a fixed cost of adoption, installation, or entry. Given a contract (r, m), the profit earned from a success is $\Pi(x(r)) - rx(r) - m - E$, while that from a failure is just $-m - E$. Hence, the firm's expected profit from the invention given a contract (r, m) and effort level e is

$$(1) \quad P_F(e, E, r, m) = p(e)[\Pi(x(r)) - rx(r)] - m - E.$$

The firm accepts this contract and attempts to commercialize the invention (after development) if and only if $P_F(e, E, r, m) \geq 0$. Note that even if the firm pays no license fees, it would not attempt to commercialize the invention if the probability of success without further inventor effort in development is "small enough," because $P_F(0, E, 0, 0) < 0$ if $p(0) < E/\Pi(x(0))$.[23] Thus, although we assume $p(0) = 0$ because it is consistent with our survey results, it is stronger than needed and could be replaced with this weaker condition.

Although effort is not contractible, it does depend on the contract (r, m). We assume that the inventor chooses effort to maximize her expected utility, and that utility takes the separable form $U_I(Y_I) - V_I(e)$, where $U_I(Y_I)$ is utility from license income Y_I and $V_I(e)$ is disutility of effort. We also assume that the marginal utility of income is positive and nonincreasing, so she is either risk averse or risk

[21] While we focus on inventor moral hazard, the licensee is also subject to moral hazard. Thus the Bayh-Dole Act includes a "march-in" provision allowing the government to take back inventions when a licensee shelves the invention rather than attempting commercialization.

[22] If $\Pi(x) = R(x) - C(x) - rx$, where $R(x)$ is total revenue and $C(x)$ is total cost, then profit-maximizing output $x(r)$ satisfies $x'(r) = [R''(x) - C''(x)]^{-1} < 0$ if $R''(x) < C''(x)$.

[23] It is worth noting that because the firm would not attempt to develop the invention on its own, the university does not need a patent in order to license the invention. This is also true for the analysis in Section IV.

neutral, and the marginal disutility of effort is positive and increasing. We allow the possibility of risk neutrality to emphasize that our results depend on moral hazard in development, not risk sharing. Thus, if α is her share of license revenue, then license income from a success is $\alpha[m + rx(r)]$, and that from a failure is αm, so her expected utility is

$$(2) \quad P_I(e, r, m) = p(e)U_I(\alpha m + \alpha rx(r)) + (1 - p(e))U_I(\alpha m) - V_I(e).$$

One feature of inventor expected utility merits further discussion. It is reasonable to assume inventors also receive utility from nonpecuniary sources, such as the utility from simply solving a puzzle or from seeing an invention commercialized (see Paula E. Stephan [1996] for a survey of empirical support). In our formulation, all nonpecuniary benefits are embodied in the disutility of effort function $V_I(e)$. Thus, we have implicitly assumed that any nonpecuniary benefits associated with development are less than those associated with other basic research projects that the inventor can undertake. That is, at the time of disclosure and licensing, the inventor has already completed the most interesting research related to the invention, so additional effort in its development involves lower nonpecuniary benefits (which we formalize as the disutility of effort in development). This assumption is consistent with our survey results. As noted in Section I, in many cases TTO managers said one of their major challenges is getting productive research faculty to disclose and continue to develop inventions beyond the proof of concept stage.

When the inventor does expend effort in development, the first-order necessary condition for maximization of expected utility is:

$$(3) \quad \frac{\partial P_I}{\partial e} = p'(e)[U_I(\alpha m + \alpha rx(r)) - U_I(\alpha m)] - V_I'(e) = 0.$$

Note that if there is no royalty, then she earns the same amount, αm, whether she expends any effort or not. Because the marginal disutility of effort is positive, she does not choose to expend effort in development unless the royalty rate is positive. However, a positive royalty rate is not sufficient to guarantee that she expends effort. This effort must result in an increase in the expected utility of income that exceeds its disutility. The firm must also accept the contract and attempt to commercialize the invention.

THEOREM 1: *Development does not occur unless the contract specifies a positive royalty rate, $e^*(0, m) = 0$. Given a positive royalty rate, the necessary condition for the inventor to expend effort in development, $e^*(r, m) > 0$ for $r > 0$, is*

$$(4) \quad p'(0)[U_I(\alpha m + \alpha rx(r)) - U_I(\alpha m)] > V_I'(0),$$

which is also sufficient if the firm accepts the contract. If development occurs:

(i) Inventor effort is decreasing in the fixed fee, $\partial e^*(r, m)/\partial m < 0$, if she is risk averse, but does not depend on the fixed fee, $\partial e^*(r, m)/\partial m = 0$, if she is risk neutral.
(ii) Inventor effort is increasing (decreasing, constant) in the royalty rate as royalty revenue is increasing (decreasing, constant) with respect to the royalty rate; $\partial e^*(r, m)/\partial r > 0(<0, =0)$ as $x + r(\partial x/\partial r) > 0(<0, =0)$.

Suppose that a contract is chosen such that the inventor undertakes development. Because the inventor receives her share of the fixed fee m before the development period, a larger fee decreases her incentive to put effort into development. That is, as long as she is risk averse, a larger m decreases the expected marginal benefit of effort, $\partial^2 P_I/\partial e \partial m < 0$, so her effort decreases. However, if she is risk neutral, then a change in the fixed fee has no effect on the expected marginal benefit of effort, and thus no effect on her effort.

The effect of a change in the royalty rate on the expected benefit of inventor effort, however, depends on its effect on royalty revenue. Suppose royalty revenue is increasing in the rate. Then an increase in the royalty rate increases the inventor's royalty income, which increases the expected marginal benefit of her effort, and so increases her effort. This is certainly the case for low enough royalty rates (i.e., $\partial[rx(r)]/\partial r = x(0) > 0$ at $r = 0$). Inventor effort therefore parallels royalty revenue as the royalty rate changes. That is, as the rate increases, both effort and revenue initially increase, reach a maximum, then decrease.

We emphasize that the assumption that inventor effort always has positive marginal disutility is stronger than necessary, and can be replaced with the assumption that there is some level of effort $e_o > 0$ such that $V_I'(e) > 0$ for all $e > e_o$ and $p(e_o) < E/\Pi(x(0))$. This implies that even if the inventor would expend effort in development without a royalty, she would never expend more than e_o. In this case, the firm would not attempt to commercialize this invention because $P_F(e_o, E, 0, m) < 0$ for any $m \geq 0$. The firm will not accept a contract unless it uses a positive royalty rate to induce the inventor to expend effort beyond e_o.

To complete the model, we must specify the objective of the TTO. Although its objective is not obvious, a priori, our survey indicates that technology managers view themselves as juggling the interests of faculty and administration. Moreover, the managers we interviewed clearly view their administration as risk averse, so we assume the payoff to the university administration (A) is given by the utility function $U_A(Y_A)$, where Y_A is its share of licensing revenue. We assume the marginal utility of income is positive and nondecreasing for the administration. Its expected utility is then

$$(5)\quad P_A(e, r, m) = p(e)U_A((1-\alpha)[m + rx(r)]) + (1 - p(e))U_A((1-\alpha)m).$$

Note that the administration's expected utility differs from the inventor's not only in the (possibly) different share of the license revenue, but also in the fact that it suffers no disutility from the inventor effort required to develop the invention to potential commercialization.

Based on the results of our survey, we assume the TTO's objective is to maximize a weighted average of the expected utilities of the administration and inventor. Assuming that the weight placed on the inventor's objectives is $\beta \in (0, 1)$, the TTO's objective function is

$$(6)\quad P(e, r, m) = \beta P_I(e, r, m) + (1-\beta)P_A(e, r, m).$$

Notice we assume that the administration cannot simply treat the inventor as an agent (in the standard principal-agent paradigm) by maximizing administration utility subject to the constraint that the inventor's utility is no less that her reservation level. As justification, we note that our surveys indicate that the vast majority of university inventions require some inventor involvement in development. Moreover, the only inventions the TTO can try to license are those disclosed by inventors. It therefore seems unrealistic to give all the "bargaining power" to the administration by treating the inventor as an agent.

The TTO's problem is then to choose a contract (r, m) to maximize its objective function subject to the licensee's participation constraint,[24] or

$$(7)\quad \text{maximize } P(e^*(r, m), r, m) \quad \text{subject to } P_F(e^*(r, m), E, r, m) \geq 0.$$

We shall consider only contracts with nonnegative royalties and fixed fees, essentially because we never observe universities subsidizing licensees. The solution to the TTO's problem thus has several possible forms. Because the royalty rate must be positive to induce effort from the inventor, the only concern is whether the

[24] This form of participation constraint implies that P_F is the licensee's expected increase in profit from the invention. If the licensee is an existing firm and the invention is a new product, then this constraint also implies that acceptance or rejection of the contract has no effect on profit from other products. Generalizing the analysis to inventions that may impact preinvention profit is beyond the scope of this paper. Our result that the optimal contract must include an output-based payment should be robust to any such generalization because it depends only on the behavior of the inventor and acceptance of the contract by the firm. This remark also applies to the analysis with sponsored research below.

solution has no fee, $m = 0$, or it is set so that the nonnegativity constraint on the licensee is binding, $m = p(e)[\Pi(x(r)) - rx(r)] - E$.

THEOREM 2: *The expected payoff to the TTO is strictly increasing in the fixed fee, for any positive royalty rate such that the firm accepts a license, if the inventor is risk neutral, or not too risk averse. Hence, if the invention has enough commercial potential that a contract is executed and development occurs, then that contract must involve both a positive royalty rate and a positive fixed fee.*

Ceteris paribus, an increase in m increases the income and expected utility of both the administration and the inventor. Thus, one expects the TTO to set the fee to extract all the "excess" expected payoff from the firm, in which case the participation constraint binds.[25] We assume (as do all principal-agent and patent-licensing models) that the firm accepts the contract and attempts to commercialize the invention if its expected payoff is 0. In our model, this is a particularly innocuous assumption because the fee paid is the expected profit from a success net of the fixed cost of commercialization, $m^* = p(e^*)[\Pi(x(r^*)) - r^*x(r^*)] - E$. Given a small probability of success, m^* is quite small, especially compared to the net profit actually earned if the invention succeeds, $\Pi(x(r^*)) - r^*x(r^*)$.

B. *Licensing by Equity*

In this section, we consider an alternative method of licensing. Although not as common as royalties, both our survey and the *AUTM Survey* (1997) indicate a dramatic increase in the fraction of license contracts involving equity ownership in the last few years. In 89 percent of our surveys, the university is allowed to hold equity in licensee-firms. The game analyzed now is exactly the same as that in the preceding section except that equity replaces royalties in the contract. In particular, the contract takes the form (ρ, m), where $\rho \in [0, 1]$ is the university's equity share, the fraction of profits from the invention to which it is entitled. The optimal level of effort chosen by the inventor is now denoted $e^*(\rho, m)$.

We assume control remains with the firm, so that the university merely collects its share of the profits without influencing the decisions made by the firm. All universities in our sample either have policies that limit the extent of equity ownership or are developing them along with conflict of interest policies. All have policies that limit the type of involvement by the inventor, with many explicitly prohibiting faculty from serving in anything other than scientific advisory roles when the university holds an equity position. An overwhelming majority also explicitly limit the equity share that the university can take (most often at 10 percent).

The equity share is simply a lump-sum transfer from the firm to the university. However, unlike the fixed fee, this transfer solves the inventor's moral-hazard problem because it is made only after she expends effort in development, the invention succeeds, and production occurs. Because optimal output in this case is $x(0)$, the firm's expected profit from the invention given a contract (ρ, m) and effort level e is now

$$(8)\quad P_F(e, E, \rho, m) = p(e)(1 - \rho)\Pi(x(0)) - m - E,$$

and the inventor's expected utility is

$$(9)\quad P_I(e, \rho, m) = p(e)U_I(\alpha m + \alpha\rho\Pi(x(0))) + (1 - p(e))U_I(\alpha m) - V_I(e).$$

The expected utility of the administration is $P_A(e, \rho, m) = p(e)U_A((1 - \alpha)[m + \rho\Pi(x(0))]) + (1 - p(e))U_A((1 - \alpha)m)$, and the TTO's problem is to choose a contract (ρ, m) to maximize $P(e, \rho, m) = \beta P_I(e, \rho, m) + (1 - \beta)P_A(e, \rho, m)$ subject to

[25] There is some possibility that, if we arbitrarily set $m = 0$, the corresponding royalty rate chosen by the TTO, r_0, is such that the firm's participation constraint binds exactly. In this case, in fact, the optimal contract is $(r_0, 0)$. Except for this razor's-edge case, we have shown that if the firm accepts the contract, it involves a positive fee.

optimal behavior by the inventor and the firm's participation constraint.[26] Again, given the positive marginal disutility of effort, the inventor does not expend effort in development unless the university's equity share is large enough.

THEOREM 3: *Development does not occur unless the contract specifies a positive equity share,* $e^*(0, m) = 0$. *Given a positive share, the necessary condition for the inventor to expend effort in development,* $e^*(\rho, m) > 0$ *for* $\rho > 0$, *is*

$$(10)\qquad p'(0)[U_I(\alpha m + \alpha\rho\Pi(x(0))) - U_I(\alpha m)] > V_I'(0),$$

which is also sufficient if the firm accepts the contract. If development occurs:

(i) Inventor effort is increasing in the equity share, $\partial e^*(\rho, m)/\partial\rho > 0$.
(ii) Inventor effort is decreasing in the fixed fee if she is risk averse, $\partial e^*(\rho, m)/\partial m < 0$, *but does not depend on the fee if she is risk neutral,* $\partial e^*(\rho, m)/\partial m = 0$.
(iii) The license contract also uses a positive fixed fee if the inventor is risk neutral, or not too risk averse.

An increase in the equity share increases the inventor's income from a success and induces her to devote more effort to development. Unlike a royalty, equity has an unambiguous effect on effort because it does not distort the firm's production decision. An increase in the royalty rate reduces output and profit from a success. An increase in the equity share has no effect on output and profit from a success, but instead merely gives the university a larger share of that profit.

Given the predominant use of royalties, and the apparent reluctance of many universities to use equity, the most interesting question is whether one method is superior.

THEOREM 4: *A contract with equity is more efficient than a contract with royalties if maximized profit from a successful invention is decreasing in the royalty rate.*

Because profit-maximizing output from a success is decreasing in the royalty rate, this result simply says that a contract with equity is Pareto superior if the output distortion introduced by royalties results in lower maximized profit (as is true for a broad class of inventions). To see this, consider the equity contract that is income equivalent to the optimal royalty rate. Let $\rho(r^*, m^*)$ be the equity share that provides the university with the same income from a success that it received under the optimal royalty rate, $\rho(r^*, m^*)\pi(x(0)) = r^*x(r^*)$. If the TTO switches from the royalty contract to this equity contract, and the inventor expends the same effort, then by construction the inventor and administration are no worse off (*ex ante*) because each anticipates the same level of expected utility. However, if maximized profit from a success is decreasing in the royalty rate, then $\pi(x(0)) > \pi(x(r^*))$, and so expected profit is greater under this income-equivalent equity contract. The optimal royalty contract is therefore Pareto inferior to this income-equivalent equity contract. The optimal equity contract is not $(\rho(r^*, m^*), m^*)$, of course, because expected profit under this contract is strictly positive. The TTO needs to adjust both the fee and equity share to attain the optimal equity contract. However, these changes simply involve reoptimization that necessarily increases the value of the TTO's objective function,[27] and cannot reduce the firm's expected profit below 0 (because it can always reject the contract). Hence, the optimal equity contract must be Pareto superior to the optimal royalty

[26] This form of participation constraint now also implies that, if the licensee is an existing firm, then acceptance or rejection of the contract has no effect on the value of the original owners' equity. As a referee has noted, an equity contract may not be Pareto superior for all inventions that have an impact on existing profits because the value of the original owner's equity may be diluted. However, the licensee could avoid this potential problem simply by commercializing the invention through a start-up in which it takes the equity position $1 - \rho$.

[27] Since the TTO maximizes a weighted average of inventor and administration utility, we cannot prove, in general, that the inventor and administration are both better off in the optimal equity contract. However, at least one must gain, and that gain must be large enough to offset any possible loss to the other. The same qualifier applies to Theorem 9.

contract. Finally, it is worth noting that expected consumer surplus is higher under the optimal equity contract because output with a successful invention is higher, $x(0) > x(r^*)$.

III. University Licensing with Sponsored Research

Another salient feature of our survey results is that sponsored research is the preferred form of compensation for faculty-inventors (recall Figure 1). Indeed, for the most embryonic inventions, it is not uncommon to observe research contracts funded by licensee-firms. Such license agreements typically have three important characteristics (see the *AUTM Technology Transfer Practice Manual, Volume II* [1993] for specific examples). One is that they grant exclusive rights to patents arising from the research support that the firm provides. They also very clearly specify the focus and content of the research project to be conducted. Finally, the firm typically assists the development process by providing funds to the university (to purchase equipment or hire support personnel, for example). Thus, in this section we consider a situation in which the licensee-firm is actively involved in development via sponsored research in the form of expenditures, S. The problem unfolds over time in the same way as before.

We assume e and S are chosen simultaneously at the beginning of the development period, after the licensing agreement has been executed. The outcome of this development game is again an updated probability of success. Given any (e, S), let $q(e, S)$ be this updated probability of success. We assume this is increasing at a decreasing rate in both its arguments, but that no amount of effort or sponsored research can guarantee success [i.e., $q(e, S) \in [0, 1)$ for all $e \geq 0$ and $S \geq 0$]. Moreover, inventions for which firms sponsor research tend to be so embryonic that both inventor effort and firm expenditure are necessary for any chance of commercial success. That is, $q(0, S) = 0$ for all $S \geq 0$ and $q(e, 0) = 0$ for all $e \geq 0$. Lastly, we assume $\partial^2 q/\partial e \partial S > 0$ for all $e \geq 0$ and $S \geq 0$ because additional expenditure 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.

A. *Licensing with Royalties*

We return to our benchmark case of contracts that specify a royalty rate and a fixed fee. Given a contract (r, m), the firm chooses expenditure on sponsored research to maximize expected profit

$$(11)\quad P_F(e, S, E, r, m) = q(e, S)[\Pi(x(r)) - rx(r)] - m - S - E,$$

and the inventor chooses effort to maximize expected utility

$$(12)\quad P_I(e, S, r, m) = q(e, S)U_I(\alpha m + \alpha rx(r)) + (1 - q(e, S))U_I(\alpha m) - V_I(e).$$

We write the Nash equilibrium outcomes of this development game as $e^n(r, m)$ and $S^n(r, m)$. In this situation the expected utility of the administration is $P_A(e, S, r, m) = q(e, S)U_A((1 - \alpha)[m + rx(r)]) + (1 - q(e, S))U_A((1 - \alpha)m)$, and the TTO's problem is to choose a contract (r, m) to maximize $P(e, S, r, m) = \beta P_I(e, S, r, m) + (1 - \beta)P_A(e, S, r, m)$ subject to optimal behavior by the inventor and firm, and the firm's participation constraint.

The first-order necessary conditions for positive choices of sponsored research by the firm and effort by the inventor are:

$$(13)\quad \frac{\partial P_F}{\partial S} = \left(\frac{\partial q}{\partial S}\right)[\Pi(x(r)) - rx(r)] - 1 = 0$$

and

$$(14)\quad \frac{\partial P_I}{\partial e} = \left(\frac{\partial q}{\partial e}\right)[U_I(\alpha m + \alpha rx(r)) - U_I(\alpha m)] - V_I'(e) = 0.$$

These define best-reply (reaction) functions. That is, (13) implicitly defines the firm's best level of sponsored research for any given level of effort, $b_F(e)$, and (14) implicitly defines the inventor's best level of effort for any given level of sponsored research, $b_I(S)$. We first note that effort and sponsored research are strategic complements because they are "complements" in development. That is, they complement each other in the "production" of a positive probability of success, $\partial^2 q/\partial e \partial S > 0$.

THEOREM 5: *Inventor effort and sponsored research are strategic complements. That is, the firm's best reply $b_F(e)$ and the inventor's best reply $b_I(S)$ are both positively sloped.*

Obviously, no development is a Nash equilibrium of this game, $(e^n, S^n) = (0, 0)$. Without inventor effort, the probability of success is zero, so the firm spends nothing on development, $b_F(0) = 0$. Similarly, without firm expenditure, this probability is zero, so the inventor expends no effort, $b_I(0) = 0$. We emphasize that, again, we make these assumptions on the probability of success because they are consistent with our survey results, not because they are necessary for this "no-development" result. This equilibrium exists whenever the probability of success is too low for either the firm or the inventor to attempt to develop the invention independently.[28] Nevertheless, because the best replies are positively sloped, it is possible that there exists another equilibrium in which development does occur, $e^n(r, m) > 0$ and $S^n(r, m) > 0$. For such an equilibrium to exist and be locally stable, it is sufficient that the best replies have the properties of those graphed in Figure 2.

THEOREM 6: *No development is a Nash equilibrium, $(e^n(r, m), S^n(r, m)) = (0, 0)$. However, if*

$$(15)\quad b'_F(0) > 1/b'_I(0),\ b''_I(S) < 0,$$
$$b''_F(e) < 0, \quad \text{and}$$
$$b'_F(e^m) = 1/b'_I(b_F(e^m)) \text{ for some } e^m > 0,$$

[28] Given a contract (r, m), from (13), $b_F(0) = 0$ if $[\partial q(0, 0)/\partial S]\Pi(x(0)) < 1$, and from (14), $b_I(0) = 0$ if $[\partial q(0, 0)/\partial e][U_I(\alpha m + \alpha r x(r)) - U_I(\alpha m)] < V'_I(0)$. Note that this is where we differ from Aghion and Tirole (1994a, b), who assume a probability of success that allows independent development by the research unit or the customer.

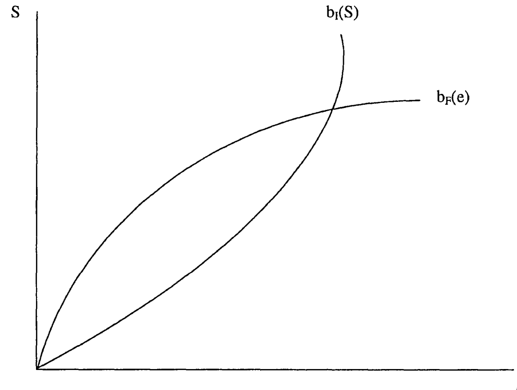

FIGURE 2. EQUILIBRIA OF THE DEVELOPMENT GAME

then there exists another Nash equilibrium with development, $e^n(r, m) > 0$ and $S^n(r, m) > 0$. Moreover, the development equilibrium is locally stable, whereas the no-development equilibrium is not.

As shown in Figure 2, the best-reply functions intersect at the origin, so that is an equilibrium. The condition $b'_F(0) > 1/b'_I(0)$ ensures that the firm's best reply is more steeply sloped than the inventor's best reply at the origin, so that this equilibrium is locally unstable. The conditions $b''_I(S) < 0$, $b''_F(e) < 0$, and $b'_F(e^m) = 1/b'_I(b_F(e^m))$ for some $e^m > 0$ guarantee that the best replies are concave enough for another intersection at $e^n(r, m) > e^m$ and $S^n(r, m) > 0$, which is a locally stable equilibrium. Naturally we are most interested in this development equilibrium, and how its existence and properties are influenced by the licensing choices of the TTO.

THEOREM 7: *Assume (15), and consider the levels of effort and expenditure in the Nash equilibrium with development, $e^n(r, m) > 0$ and $S^n(r, m) > 0$.*

(i) Equilibrium effort and sponsored research are decreasing in the fixed fee, $\partial e^n(r, m)/\partial m < 0$ and $\partial S^n(r, m)/\partial m < 0$, if the inventor is risk averse, but do not depend on the fixed fee, $\partial e^n(r, m)/\partial m = 0$ and $\partial S^n(r, m)/\partial m = 0$, if the inventor is risk neutral.
(ii) In general, changes in the royalty rate have an ambiguous effect on equilibrium effort

and sponsored research. However, they are decreasing in the royalty rate, $\partial e^n(r, m)/\partial r < 0$ and $\partial S^n(r, m)/\partial r < 0$, if the inventor's best-reply effort is decreasing in the royalty rate, which occurs only for those rates such that royalty revenue is also decreasing in the royalty rate.

Suppose the inventor and firm undertake development. Comparative statics with respect to the fixed fee are similar to those in the benchmark case of Section II, subsection A. The inventor's best reply is affected by a change in the fixed fee only if she is risk averse, in which case it rotates back to the left (effort decreases for all $S > 0$). Since the firm's best reply does not depend on the fixed fee, a change in it has no effect on equilibrium effort or sponsored research when the inventor is risk neutral.

However, a change in the royalty rate affects both firm profit and inventor income. An increase in the rate decreases the firm's profit from a success, and thus its expected marginal benefit from sponsored research. Hence, an increase in r decreases sponsored research for all $e > 0$. Ceteris paribus, because they are strategic complements, inventor effort also tends to decrease. However, other things are not equal because the increase in r also changes royalty income. In a fashion similar to our benchmark case, the effect of a change in r on the marginal benefit of effort parallels royalty revenue as the royalty rate changes. As long as profit-maximizing output is inelastic with respect to the royalty rate, both royalty revenue and the expected marginal benefit of effort increase with an increase in r, so effort increases for all $S > 0$. Again, because they are strategic complements, sponsored research tends to increase. The net effect, of course, is ambiguity [consider Figure 2 when $b_F(e)$ rotates down and $b_I(S)$ rotates to the right].

These results suggest that, as in our benchmark case, the use of output-based payments such as royalties is essential in the development of embryonic inventions. The reason remains that inventor effort is required for any chance of success. As long as the inventor's effort in development is not contractible and causes disutility, there is a moral-hazard problem that cannot be solved by contracts relying only on lump-sum payments such as fixed fees or sponsored research.

THEOREM 8: *No development is the unique equilibrium if the license contract does not specify a positive royalty rate. That is, a positive royalty rate is a necessary condition for development to occur in equilibrium: $e^n(r, m) > 0$ and $S^n(r, m) > 0$ only if $r > 0$. The contract also must involve a positive fixed fee if the inventor is risk neutral or not too risk averse.*

If the inventor is risk neutral, or not too risk averse, then the TTO's objective function is strictly increasing in the fixed fee for any positive royalty rate. Hence, if the invention has enough commercial potential that a contract is executed and development occurs, then that contract must involve both a positive royalty rate and fixed fee.

B. *Licensing with Equity*

Finally, we consider equity as an alternative to royalties in the presence of sponsored research. The TTO chooses a contract (ρ, m) to maximize its expected payoff subject to optimal behavior by the inventor and the firm, and the firm's participation constraint. Compared to equity contracts without sponsored research, one important difference is that an increase in the equity share does not necessarily increase inventor effort. This is particularly interesting because, as in the case of equity without sponsored research, an increase in equity increases the inventor's marginal expected utility. This induces the inventor to provide more effort for any positive level of sponsored research. However, because the increase in equity decreases the firm's marginal expected payoff, the firm provides less sponsored research for any positive level of effort. Because effort and sponsored research are strategic complements, in equilibrium the effect on inventor effort is ambiguous. This can be easily seen from Figure 2, noting that the firm's best reply rotates down and the inventor's best reply rotates to the right.

THEOREM 9: *In the development game with an equity contract, no development is the unique equilibrium if the contract does not* *specify a positive equity share. Under a condition on best replies analogous to (15), there exists a locally stable development equilibrium in which:*

(i) Changes in the equity share have an ambiguous effect on inventor effort and sponsored research.
(ii) Inventor effort and sponsored research are decreasing in the minimum fee if the inventor is risk averse, but do not vary with the fee if the inventor is risk neutral.
(iii) The contract must involve a positive minimum fee if the inventor is risk neutral or not too risk averse.
(iv) Even in the presence of sponsored research, an equity contract is more efficient than a royalty contract if maximized profit from a success is decreasing in the royalty rate.

IV. Concluding Remarks

In the debate surrounding the Bayh-Dole Act, proponents argue that unless universities have the right to license faculty inventions, many results from federally funded research would remain in the research lab, finding industrial application only after a significant delay, if at all. In an effort to shed light on this debate, we surveyed technology managers from 62 universities about invention characteristics, licensing procedures, and licensing objectives in their universities. Our results show that the vast majority of inventions licensed are so embryonic that technology managers consider inventor cooperation in further development crucial for commercial success. These managers also reported challenges associated with inducing such cooperation from research faculty. Thus, for these inventions, there is a moral-hazard problem with regard to inventor effort. Our theoretical analysis shows that development would not occur unless the inventor's return is tied to the licensee's output when the invention is successful. This can be done with royalties, and in fact, our survey results show that the vast majority of agreements include royalty payments. Increasingly, however, technology managers are including equity participation by the university. In fact, we show not only that equity can induce inventor cooperation, but also that contracts with equity are Pareto superior to those with royalties. We also focused on the role of sponsored research in situations where inventions could not be successful without licensee expenditure early on in the process. We find essentially the same results, which implies that sponsored research alone cannot solve the moral-hazard problem.

Opponents of Bayh-Dole, conversely, argue that no additional incentives are required to commercialize important inventions, and that it may divert faculty from more basic research and teaching. An important case we have not examined is when the inventor starts a company based on an invention developed in the course of her research, owns founder shares in the firm, and retains her job at the university. Because she holds equity in the licensee and receives a share of license revenue, there is a potential conflict of interest that we do not address. There is also a potential conflict of commitment in that the university administration may not view her allocation of time between university and firm responsibilities as appropriate. Addressing the latter issue requires extending our model to include the disutility of inventor effort in the administration's utility function. We have also not considered the case where the inventor has employment opportunities other than the university. For example, there may be a trade-off between royalties and inventor salaries that universities exploit in attracting faculty. In future work, we plan to explore these and other aspects of our survey not reported in this paper.

Appendix A: Survey Design Sample

Questionnaires were sent to the top 135 universities in terms of licensing revenue according to the 1996 *AUTM Survey*, and responses were received from 62 universities: Alabama, Birmingham; Arizona State; Baylor; California, Berkeley; California, Los Angeles; California, San Diego; California, San Francisco; California, System Office; California Institute of Technology; Carnegie Mellon; Chicago; Cincinnati; Clemson; Colorado State; Colorado; Columbia; Dartmouth College; Dayton; Duke; Emory; Florida Atlantic; Florida State; Georgia Institute of Technology; Harvard; Illinois, Urbana/Champaign; Indiana; Iowa State; Johns Hopkins; Kentucky; Lehigh; Marquette; Massachusetts Institute of Technology; Michigan

State; Michigan Technological; Michigan; Minnesota; Mississippi State; Missouri; New Jersey Institute of Technology; New Mexico State; North Carolina, Chapel Hill; Northwestern; Ohio State; Pennsylvania State; Pennsylvania; Purdue; Rhode Island; Rochester; Rutgers; Stanford; State University of New York; Tennessee; Texas A&M; Thomas Jefferson; Tulane; Utah; Virginia Tech; Wake Forest; Washington; Wisconsin; Woods Hole; and Yale.

Questionnaire

The content of our questionnaire was influenced by: (i) the policy debate over the impact of the Bayh-Dole Act, and, in particular, the role of university licensing practices on the industrial impact of university research; (ii) potential conflicts between the objectives of inventors and technology transfer managers; and (iii) our interest in determining whether university licensing practices are consistent with results from the theoretical literatures on optimal contracts and patent licensing.

To maximize the likelihood that questions were interpreted accurately and that respondents could provide reliable information, we pretested the questionnaire on 11 experienced university technology transfer managers. These managers came from a mixture of private and public universities. The majority of managers in our test group had at least ten years of experience in university technology transfer. Each individual was asked to complete the test questionnaire for his own institution and to think about whether technology managers with less experience or from a variety of universities would be able to answer the questions. All individuals in the test group were interviewed face-to-face, and all questions in the questionnaire were discussed to minimize ambiguity. For the actual survey, follow-up telephone interviews were also used to minimize ambiguity.

There is undoubtedly noise in the survey data. In part, this is because respondents provided estimates of quantitative data which were not available from university files, but also because a number of our questions require judgment about quantitative data. Consider, for example, the question: "What percentage of the invention disclosures licensed in the last five years were in the following stages of development at the time the license agreement was executed?" Few universities maintain files providing such information, but even so, managers' responses may be in error either because the true stage of development was misjudged or because respondents perceive questions differently. To minimize errors of this type, we used the categories listed in Table 1, part 5, all of which were identified by our test group as standard for evaluating stage of development.

For questions with a semantic scale (categorical questions), respondents may indeed perceive the same environment but use the scale differently. To minimize error of this type, we based the scale underlying Figure 1 on research results from the literature on optimal rating scales. As discussed by Jon A. Krosnick and Leandre R. Fabrigar (1997), research on the reliability of rating scales suggests people can distinguish among and have consistent interpretations of the four-point scale, "extremely important," "moderately important," "not very important," and "not applicable." One problem with this scale for our purposes is that we are interested in the importance of five outcomes that our test group suggested are the major criteria used by technology transfer offices to measure their success. Note that this necessarily implies tied responses for rankings of some outcomes.

Finally, items in Table 2 (except for part 2) are based on respondent estimates of the frequency of an event or contract term. Managers were asked to identify the frequency as "almost always," "often," "sometimes," "rarely," or "never." To quantify the responses, we assigned numerical values according to values reported by Frederick Mosteller and Cleo Youtz (1990) for the average value assigned to these terms in 20 studies on probabilities associated with categorical data. Values assigned were 0.91 for almost always, 0.65 for often, 0.28 for sometimes, 0.09 for rarely, and 0.01 for never.

Appendix B: Sketches of Proofs

In this Appendix, we provide brief sketches of the proofs for Theorems 1–9. Complete proofs are available from the authors.

PROOF OF THEOREM 1:

If $r = 0$, then $P_I(e, 0, m) = U_I(\alpha m) -$

$V_I(e)$ is maximized for $e \geq 0$ at $e = 0$ because $V_I'(e) > 0$ and $V_I''(e) > 0$ for $e \geq 0$. If $r > 0$, then $P_I(e, r, m)$ is maximized at some $e > 0$ because (4) implies $\partial P_I/\partial e > 0$ at $e = 0$ and $\partial^2 P_I/\partial e^2 < 0$ for $e \geq 0$. We must also assume the firm accepts the contract (otherwise the inventor expends no effort). Ordinary comparative statics on (3) gives (*i*) and (*ii*).

PROOF OF THEOREM 2:

Theorem 2 follows from observing that $\partial P(e^*(r, m), r, m)/\partial m > 0$ if the inventor is risk neutral because $\partial P_I/\partial m > 0$, $\partial P_A/\partial e > 0$, $\partial P_A/\partial m > 0$, and $\partial e^*(r, m)/\partial m = 0$ by Theorem 1. Because $\partial P(e^*(r, m), r, m)/\partial m > 0$ for $\partial e^*(r, m)/\partial m < 0$ but small enough, the same result holds if the inventor is not too risk averse.

PROOF OF THEOREM 3:

If $\rho = 0$, then $P_I(e, 0, m) = U_I(\alpha m) - V_I(e)$ is maximized for $e \geq 0$ at $e = 0$. If $\rho > 0$, then $P_I(e, \rho, m)$ is maximized at some $e > 0$ because (10) implies $\partial P_I/\partial e > 0$ at $e = 0$ and $\partial^2 P_I/\partial e^2 < 0$ for $e \geq 0$. Thus (*i*) and (*ii*) follow from comparative statics on the first-order necessary condition $\partial P_I/\partial e = p'(e)[U_I(\alpha m + \alpha\rho\Pi(x(0))) - U_I(\alpha m)] - V_I'(e) = 0$. Differentiating $P(e^*(\rho, m), \rho, m)$ with respect to m and using (*ii*) gives (*iii*) since $\partial P_I/\partial m > 0$, $\partial P_A/\partial e > 0$, and $\partial P_A/\partial m > 0$.

PROOF OF THEOREM 4:

Consider the optimal royalty contract (r^*, m^*) and the resulting inventor effort $e^*(r^*, m^*)$ defined by (3). Let $\rho(r^*, m^*)$ be the equity share that provides the same income from a success as under the optimal royalty, $\rho(r^*, m^*)\pi(x(0)) = r^*x(r^*)$. If the TTO switches from the royalty contract to this income-equivalent equity contract, and if the inventor expends the same effort $e^*(r^*, m^*)$, then by construction the inventor and university administration are no worse off (*ex ante*) because each has the same expected utility. However, if maximized profit from a success is decreasing in the royalty rate, then $\pi(x(r^*)) < \pi(x(0))$ and the firm earns more profit from a success, $[1 - \rho(r^*, m^*)]\pi(x(0)) > \pi(x(r^*)) - r^*x(r^*)$. Hence, expected profit is also greater under the income-equivalent equity contract with the same level of effort, $p(e^*(r^*, m^*))[1 - \rho(r^*, m^*)]\pi(x(0)) - m^* - E > p(e^*(r^*, m^*))[\pi(x(r^*)) - r^*x(r^*)] - m^* - E$. The optimal royalty contract is thus Pareto inferior to the income-equivalent equity contract when the inventor expends the same effort under both. The optimal equity contract is not $(\rho(r^*, m^*), m^*)$. Because expected profit under this contract is strictly positive, the TTO must adjust both the fixed fee and equity share to attain the optimal equity contract. The resulting contract is Pareto superior to the optimal royalty contract since the reoptimization cannot reduce the firm's expected profit below 0 (the firm can always reject it) and it must increase the value of the TTO's objective function.

PROOF OF THEOREM 5:

From (13), $b_F'(e) = -(\partial^2 P_F/\partial S\partial e)/(\partial^2 P_F/\partial S^2) > 0$ because $\partial^2 P_F/\partial S\partial e > 0 > \partial^2 P_F/\partial S^2$. Similarly, from (14), $b_I'(S) = -(\partial^2 P_I/\partial e\partial S)/(\partial^2 P_I/\partial e^2) > 0$ because $\partial^2 P_I/\partial e\partial S > 0 > \partial^2 P_I/\partial e^2$.

PROOF OF THEOREM 6:

Because $q(e, 0) = 0$ for $e \geq 0$, $P_I(e, 0, r, m) = U_I(\alpha m) - V_I(e)$ is maximized for $e \geq 0$ at $e = 0$, and so $b_I(0) = 0$. Similarly, because $q(0, S) = 0$ for $S \geq 0$, $P_F(0, S, E, r, m) = -S - E - m$ is maximized for $S \geq 0$ at $S = 0$, and so $b_F(0) = 0$. Hence, $(e^n, S^n) = (0, 0)$ is an equilibrium.

Given $f(e) = b_I(b_F(e)) - e$, (e^n, S^n) is a Nash equilibrium if and only if $f(e^n) = 0$ and $S^n = b_F(e^n)$, and it is locally stable if and only if $b_I'(S^n)b_F'(e^n) < 1$. One can show that (15) implies (0, 0) is not a locally stable equilibrium, and there exists another Nash equilibrium $(e^n(r, m), S^n(r, m))$ with $e^n(r, m) > e^m > 0$ and $S^n(r, m) > 0$, which is locally stable.

PROOF OF THEOREM 7:

Theorem 7 follows from comparative statics on (13) and (14) and the observation that $\partial^2 P_F/\partial S\partial m = 0$, $\partial^2 P_F/\partial S^2 < 0$, $\partial^2 P_F/\partial S\partial e > 0$, $\partial^2 P_I/\partial e\partial m < 0$ if $U_I'' < 0$ but $\partial^2 P_I/\partial e\partial m = 0$ if $U_I'' = 0$, $\partial^2 P_F/\partial S\partial r < 0$ from the envelope theorem, $\partial^2 P_I/\partial e\partial r \leq 0$ only if $x + r(\partial x/\partial r) < 0$, and $(\partial^2 P_F/\partial S^2)(\partial^2 P_I/\partial e^2) > (\partial^2 P_F/\partial S\partial e)(\partial^2 P_I/\partial e\partial S)$ by local stability.

PROOF OF THEOREM 8:

From (12), if $r = 0$, then $P_I(e, 0, m) = U_I(\alpha m) - V_I(e)$ is maximized at $e = 0$ for all S, so $b_I(S) = 0$ for all S. From (11), $P_F(0, S, E, r, m) = -m - S - E < 0$ is maximized at $S = 0$ for all e, so $b_F(0) = 0$ for all e.

Hence, $(e^n(0, m), S^n(0, m)) = (0, 0)$ is the unique Nash equilibrium for any $m \geq 0$, whence $r > 0$ is a necessary condition for an equilibrium with development. The contract involves a positive fixed fee if the inventor is risk neutral or not too risk averse because $\partial P(e^n(r, m), S^n(r, m), r, m)/\partial m > 0$ as in Theorem 2.

PROOF OF THEOREM 9:

In this development game the firm's expected profit is $P_F(e, S, E, \rho, m) = q(e, S)(1 - \rho)\Pi(x(0)) - m - S - E$, the inventor's expected utility is $P_I(e, S, \rho, m) = q(e, S)U_I(\alpha m + \alpha\rho\Pi(x(0))) + (1 - q(e, S))U_I(\alpha m) - V_I(e)$, the university's expected utility is $P_A(e, S, \rho, m) = q(e, S)U_A((1 - \alpha)(m + \rho\Pi(x(0)))) + (1 - q(e, S))U_A((1 - \alpha)m)$, and the TTO's expected payoff is $P(e, S, \rho, m) = \beta P_I(e, S, \rho, m) + (1 - \beta)P_A(e, S, \rho, m)$.

Given an equity contract, the first-order necessary conditions for positive choices of sponsored research and effort are $\partial P_F/\partial S = (\partial q/\partial S)(1 - \rho)\Pi(x(0)) - 1 = 0$ and $\partial P_I/\partial e = (\partial q/\partial e)[U_I(\alpha m + \alpha\rho\Pi(x(0))) - U_I(\alpha m)] - V_I'(e) = 0$. These implicitly define best-reply functions, which are strategic complements as in Theorem 5. The proof that no development is an equilibrium, but there also exists a locally stable development equilibrium under a condition similar to (15), is analogous to the proof of Theorem 6. Then (*i*) and (*ii*) follow from comparative statics on $\partial P_F/\partial S = 0$ and $\partial P_I/\partial e = 0$, the observation that $\partial^2 P_F/\partial S\partial m = 0$, $\partial^2 P_I/\partial e\partial m < 0$ if $U_I'' < 0$ but $\partial^2 P_I/\partial e\partial m = 0$ if $U_I'' = 0$, $\partial^2 P_F/\partial S\partial\rho < 0$, and $\partial^2 P_I/\partial e\partial\rho > 0$, and local stability. The proof that no development is the unique equilibrium without a positive equity share and (*iii*) is analogous to the proof of Theorem 8, and the proof of (*iv*) is analogous to that of Theorem 4.

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