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Appropriability and Commercialization: Evidence from MIT Inventions

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Abstract

At least since Arrow (1962), the effects of appropriability on invention have been well studied, but there has been little analysis of the effect of appropriability on the commercialization of existing inventions. Exploiting a database of 805 attempts by private firms to commercialize inventions licensed from MIT between 1980 and 1996, we explore the influence of several appropriability mechanisms on the commercialization and termination of projects to develop products based on university inventions. We construct a theoretical model in which the licensee faces technical and market uncertainty, and anticipates that its products will be imitated. We characterize the hazards of commercialization and termination as functions of appropriability mechanisms, including patent scope and the effectiveness of patents as well as learning, lead time, and secrecy in attaining competitive advantage. The model is tested using a competing risks framework that allows for non-parametric unobserved heterogeneity and correlated risks. In our sample, patent strength and secrecy influence termination decisions, while learning, patent scope and lead time influence commercialization decisions.

Keywords: Hazard rates, Innovation, Optimal stopping problem, Patent scope, University licensing, Termination
JEL numbers: O31, O34

1 Introduction

Do strong intellectual property rights enhance the commercialization of new technology? Surprisingly, we do not know the answer to this question (Gallini 2002). Although the role of property rights in innovation has been studied extensively since Arrow (1962) argued that firms underinvest in R&D because they cannot fully appropriate the returns, much of this work focuses on the effect of property rights, particularly those associated with patents, on inventive activity. There has been little analysis of the effect of appropriability mechanisms on the commercialization of existing inventions (Hahn 2003). As firms increasingly rely on externally generated inventions, particularly those invented and patented by universities, this omission represents an important gap in our understanding (Santoro and Chakrabarti 2002, Thursby and Thursby 2003). Furthermore, given the strong evidence that intellectual property rights are imperfect in their ability to deter imitation, it is important for managers in-licensing inventions to understand the role of a broad range of mechanisms to appropriate the returns to commercializing these inventions.

In this paper, we exploit a unique database that allows us to examine the relationship between appropriability mechanisms and the outcomes of commercialization efforts in the context of university patent licensing. We examine the population of 805 attempts by private firms to commercialize patentable inventions licensed from the Massachusetts Institute of Technology between 1980 and 1996. We use information obtained from the MIT Technology Licensing Office (TLO) on whether the invention was commercialized, and if so, the date of first sale, and the date of termination if the license was terminated. We augment this information with data on patent scope, measures of patent effectiveness and other means of appropriating returns to innovation, such as secrecy, learning, and lead time.

To derive hypotheses for the empirical analysis, we construct a theoretical model of the decisions faced by a firm that has exclusively licensed a patentable university invention.[1] Reflecting the embryonic nature of most university inventions, we assume

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[1] The theoretical literature on optimal R&D investment and the diffusion of innovation is vast. A number of papers deal with questions closely related to the topic of this paper, such as the optimal amount of R&D investment under potential competition in the product market (Kamien and Schwartz, 1971 and 1974), the optimal timing of innovation with strategic interactions between firms (for instance, Reinganum, 1980 and 1981; Katz and Shapiro, 1987; Waterson, 1990 and more recently, Jensen, 2003 and Hoppe and Lehmann-Grube, 2005, which also provides a short survey of this literature) or in

that further development is needed before a product based on the invention can be commercialized. A key ingredient of the model is that the returns to this development are subject to both technical and market uncertainty (Thursby and Thursby 2002, Shane 2000). The firm also anticipates entry by other firms with products based on non-infringing substitutes for the invention. Thus, despite patent protection, the firm knows that it is unlikely to obtain monopoly profits throughout the life of the patent. The window during which the firm earns monopoly profits, or lead time, depends on the cost of non-infringing imitation. The importance of lead time to the firm is a function of the difference between these monopoly profits and duopoly profits once a competitor enters. Following Mansfield et al.'s (1981) study, we view the competitor's imitation costs as being positively related to the level of protection offered by the patent (patent strength), its scope, and the effectiveness of secrecy.

In our model, in each period, the firm decides whether to invest in further development of the invention, increasing the technical probability of success, or to terminate the project. Contingent on technical success, the firm decides when to commercialize the invention. The model is constructed to characterize the hazard of the firm terminating development in any period, as well as the hazard of commercializing in any period. The existence of technical and market uncertainty, reflected by shocks to development cost and profit shocks respectively, allows us to express both the hazards of termination and commercialization as functions, not only of time, but also the firm's ability to appropriate the returns from developing a marketable product based on the invention.

Since higher imitation costs result in delayed entry by a competitor and, therefore, higher expected returns from the licensed innovation, it is not surprising that we find the hazard of the firm terminating a license to be decreasing in the date of entry by a competitor. Better appropriability (in the sense of wider patent scope, more effective patent strength and more effective secrecy) therefore results in a lower hazard of termination because of its negative effect on the speed at which imitators can catch up.

The relationship between commercialization and various measures of appropriability is less straightforward, since the firm may or may not commercialize the invention as soon as technical success is determined. As is well known from the product development literature, firms may introduce products quickly to take advantage of a market opportu-

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a decision-theoretic framework (for instance, Kamien and Schwartz, 1972; Jensen, 1982 and recently, Takalo and Kanniainen, 2000). Our model borrows substantially from the modeling choices made by several of these authors.

nity or delay because realized profit early on may be low (see Lilien and Yoon, 1990 and Bayus et al., 1997). When taking potential imitation into account, and under the assumption that commercialization discloses important information about the technology to potential competitors, the firm must weigh realized current profit with the potential for imitation. In our model, we show that waiting is optimal when the realized profit in the period of technical success is below a threshold that we characterize, even though the firm never expects that it will delay commercialization. This outcome is more likely to happen when the ability to appropriate returns is low.

We find the hazard of commercialization to be positively related to appropriability mechanisms that raise imitation costs. This is because, other things being held constant, the longer the firm anticipates earning monopoly profits, the more readily it tolerates a low profit level initially. Thus, in this case, a wide range of initial profit realizations are consistent with the firm's decision to commercialize immediately rather than to wait. A similar result holds regarding the role of learning in appropriating returns. The more important learning is, the less the difference between monopoly and duopoly profit to the licensee, but also the lower the profit to a competitor and, thus, the later the date of entry. These effects imply that when learning is important, the hazard of commercialization is higher.

On the other hand, the hazard of commercialization is decreasing in the importance of lead time in appropriating returns. The lead time before imitation contributes more to the firm's overall return from commercialization the larger is the difference between monopoly and duopoly profits in each period. Thus, for inventions that yield a relatively low return once imitated, the threshold above which commercialization occurs is higher. In this situation, lead time is relatively important in appropriating returns, and the range of acceptable initial monopoly profit realizations for commercialization is smaller, ceteris paribus.

The empirical analysis is based on a competing risks hazard model which allows correlated risks and unobserved heterogeneity. The empirical results support most of the model's predictions for both termination and commercialization. The hazard of termination is decreasing in secrecy and patent strength, and this finding is robust across specifications. An increase patent scope has a negative effect on termination, though this effect is not statistically significant.

With respect to commercialization, the hazard rate is increasing in patent scope and the importance of learning, as predicted by the model. Further, we find robust support for our novel theoretical result that the hazard of commercialization is decreasing in the importance of lead time. Finally, although positive, the relationships between patent strength and secrecy and the hazard of commercialization are not statistically significant.

By showing, both theoretically and empirically, that several dimensions of appropriability affect the hazards of project termination and technology commercialization, we contribute to the literature on appropriability and innovation. Our results on patent strength contribute to the extensive literature on patents and innovation (for a survey, see Gallini, 2002). By treating the decision to commercialize an invention as an optimal stopping problem with technical uncertainty, we examine patent scope and innovation in a way that incorporates the possibility of termination, which, though quite relevant to embryonic technologies licensed to firms, has been ignored in the literature.[2] Furthermore, we contribute to the empirical literature on the effectiveness of patents in appropriating the returns from R&D by directly examining the relationship between patent characteristics and the development of products based on newly invented technologies, rather than relying on perceptions of R&D personnel responding to surveys (Taylor and Silberston, 1973; Mansfield, 1986; and Mansfield et al, 1981). Finally, by focusing on the difference between monopoly and duopoly profits as a measure of the importance of lead time, we are able to derive, and test empirically, the nontrivial result that the hazard of commercialization is decreasing in the importance of lead time.

Our theoretical analysis also extends the literature on product development and management. For example, Lilien and Yoon (1990) and Bayus et al. (1997) show that it may be optimal for market pioneers to delay product launch depending on demand characteristics, as well as market competition. Our model provides a rationale for the timing of

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[2] We assume discrete time to be able to explicitly characterize hazard rates of termination and commercialization and perform comparative statics on several measures of appropriability. Solutions to general optimal stopping problems have been characterized by Roberts and Weitzman (1980). See Dixit and Pindyck (1994) for a discussion of the complexity involved in characterizing the distribution of the optimal stopping time in continuous time models with uncertainty, and thus, the hazard rate of the stopping decision. See also Marco (2003) for an application somewhat related to our paper in which comparative statics rely on simulations. Kamien and Schwartz (1971), Grossman and Shapiro (1986) and Goel (1996) among others have analyzed the problem of a firm with the opportunity to invest in a R&D project of unknown difficulty, so that in their models, terminating the project is an option for the firm. However, they also assume that the reward is known so that the decision to commercialize once successful is trivial. Our model is similar to Takalo and Kanniainen (2000) since we treat the decision to commercialize as an optimal stopping problem, but we differ substantially in that our problem includes technical uncertainty so that termination is a realistic option for the firm.

product launch in the context of appropriabilty mechanisms. In this regard, our analysis adds to the literature on commercialization strategy as well. For example, Gans, Hsu and Stern (2003) examine whether startup innovative firms commercialize their innovations independently or by partnering with other firms as a function of patent rights, secrecy, or the litigation environment as measures of the appropriability regime. Both our theoretical and empirical results add to this literature by considering other measures of appropriability and the timing of independent commercialization.

Finally, we contribute to the practice of technology management and strategy by developing and then testing a model of how managers should make decisions about investing in the development of inventions or terminating R&D projects as a function of the ways that the returns to that investment can be appropriated. We explain and show that managers should think differently about appropriability conditions in making project termination and technology commercialization decisions because appropriability conditions affect the two types of decisions in very different ways. Moreover, our model and our empirical test both indicate when managers should delay commercialization as a way to enhance returns. Given the increasing reliance of firms on externally-generated inventions, particularly those developed in universities, this information should be useful to managers in technology-intensive industries.

In section 2 we describe the model and derive the comparative statics results on appropriability measures. In sections 3 through 5, we present the data and empirical results. Section 6 concludes.

2 Theoretical Model

In this section, we consider the problem faced by a firm (henceforth, “the licensee”) that has exclusively licensed a patented university invention which requires further development before it can be commercialized. The returns to the licensee are subject to technical as well as market uncertainty. By technical uncertainty, we refer to the likelihood that the invention works. The existence of such uncertainty is supported by a recent survey of businesses that license-in university inventions in which respondents reported that 47% of the licensed inventions that failed did so for purely technical reasons (Thursby and Thursby, 2003). This is hardly surprising since roughly half of university inventions licensed are no more than a proof of concept at the time of license (Jensen and Thursby, 2001, and Thursby et al., 2001).

Market uncertainty exists for several reasons. First, defining market opportunities for early stage inventions is difficult, so much so that many university inventions end up with applications that are not anticipated at the time of license (Shane, 2000, and Thursby and Thursby, 2002). Second, even though the exclusive patent license guarantees a legal monopoly on market applications of the invention, it provides no guarantee against other firms developing substitutes or inventing around the patent.

2.1 Optimal development and commercialization

To successfully commercialize the invention, the licensee must invest $C_t = c + \tilde{\epsilon}_t$ per period, where the random cost shock $\tilde{\epsilon}_t$ is i.i.d. according to a continuously differentiable c.d.f. $G(\tilde{\epsilon})$ with zero mean and defined on a non-empty interval $[\underline{\epsilon}, \overline{\epsilon}]$.[3] The running development cost c includes not only internal costs but also payments to the university, such as milestones, minimum royalties, and sponsored research. The probability of technical success in period t is q_t. While investment may not increase the probability of success in any period, it is natural to assume that the sequence of probabilities q_t is non-decreasing.[4]

We assume the life of the patent on the licensed technology is $L > 1$. As in Takalo and Kanniainen (2000), the licensee faces exogenous market uncertainty as well as potential competition from a follower selling a non-infringing substitute. When the licensee has a monopoly in the market for its product, its profit in period t, denoted by $\tilde{\pi}_t^m$, is a random variable with c.d.f. $F_t^m(\tilde{\pi}_t^m)$. If the licensee faces competition in period t, then its profit is given by the random variable $\tilde{\pi}_t^d$ with c.d.f. $F_t^d(\tilde{\pi}_t^d)$. Importantly, we assume $\pi_t^m \equiv E[\tilde{\pi}_t^m] > E[\tilde{\pi}_t^d] \equiv \pi_t^d$, as well as $\pi_t^d \geq 0$, that is, expected monopoly profit is strictly greater than expected duopoly profit and both are positive. Finally, for interest rate r, $\delta = (1 + r)^{-1} < 1$ is the licensee's discount rate.

The timing of events in a given period is as follows. The licensee observes the realization of the cost shock, ϵ_t, and must decide whether to invest $c + \epsilon_t$ or to terminate. If the licensee invests, but this investment yields a technical failure, the licensee observes a new cost shock and again, decides whether to invest or to terminate. If investment yields

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[3] In the continuation, we assume $\underline{\epsilon} > -c$.

[4] Thus we assume q_t is the true probability of success. An alternative, and more complicated model, would allow the licensee's perceived probability of success to differ from the true probability. In that case, investment could yield positive or negative observations which would be used to update the firm's perceived (prior) probability according to Bayes Rule.

a technical success, the licensee observes the realization of profit for the current period and must decide whether to commercialize or to wait. If it decided to wait in period t, then it observes the profit realization for the next period, when again, it decides whether to commercialize or to wait.

We begin by analyzing the decision to terminate or continue to work on the project prior to technical success. To this effect, let V_t denote the expected value from commercializing optimally given that technical success was achieved in period t. At this point, it is useful to make the following intuitive assumption in order to characterize the value of continuing to invest, $V_c(\epsilon_t, t)$. We maintain this assumption throughout the remainder of the analysis.

Assumption 1. There exists a period of time $\overline{L}$ such that for $t \leq \overline{L}$, there is non-zero probability that the value of continuing to invest will be strictly positive and for $t > \overline{L}$, the value of continuing to invest is equal to zero with probability one. That is, $q_{\overline{L}} V_{\overline{L}} \geq c + \underline{\epsilon}$ and for all $t > \overline{L}$, $q_t V_t < c + \underline{\epsilon}$.

Under Assumption 1, a standard dynamic programming argument implies that given a cost shock ϵ_t, the value of the project in period t is equal to

$$V_c(\epsilon_t, t) = \max \left\{ -c - \epsilon_t + q_t V_t + \sum_{n=1}^{\overline{L}} \delta^n \prod_{i=0}^{n-1} (1 - q_{t+i})(q_{t+n} V_{t+n} - c), 0 \right\}. \tag{1}$$

The value of continuing to invest given by equation (1) has a straightforward interpretation. After subtracting the cost of development at period t, it is equal to the probability of being successful in period t times the value of commercializing optimally thereafter, plus the expected value of being successful in a later period minus the expected development cost.

To determine the conditions under which the licensee terminates development, we define

$$\Delta_t \equiv -c + q_t V_t + (1 - q_t) \delta E V_c(\tilde{\epsilon}_{t+1}, t+1). \tag{2}$$

If $\epsilon_t > \Delta_t$, the licensee terminates in period t, whereas if $\epsilon_t \leq \Delta_t$, it continues; that is, the licensee continues as long as the expected value of doing so is greater than the random cost shock.

We now characterize V_t by considering the licensee's optimal commercialization decision problem. The date at which a rival may enter and commercialize a product based on a non-infringing technology is endogenous to the extent that an entrant can reverse engineer and invent around the licensed technology. If the licensee first commercializes at $t \leq L$, we assume it correctly determines that successful imitation by an entrant will take place in period λ_t.[5] Hence $\lambda_t - t$ represents the licensee's lead time, or the time window during which the licensee receives monopoly profit from selling the invention, if it commercializes in period t. We assume that $L + 1 > \lambda_t > t$ holds. In other words, imitation occurs strictly after the date of first sale and no later than the period following the patent's expiration date. We also assume that λ_t does not decrease with t. Implicitly we are assuming that dissemination of information required for successful imitation occurs through the commercialization of a product by the licensee (Takalo and Kanniainen, 2000). The follower's entry time is clearly a function of other variables besides the licensee's first date of sale t. It will generally depend on any factor related to how difficult non-infringing imitation is, such as the cost of development of such imitation and the expected profit from marketing it. We note that the realistic assumption that the licensee cannot perfectly forecast profit levels allows us to generate a rich set of implications regarding commercialization. Indeed, in the absence of market uncertainty, the decision to commercialize would be trivial. If the certain cumulative profit decreased over time, then the licensee would commercialize immediately following technical success. Otherwise the firm would simply wait until the date at which cumulative profit was the highest. The probability that the firm would commercialize at that date would thus equal one, while it would be zero in other periods.

Under these assumptions, in the period in which the first sale occurs, the licensee acts as a monopolist, so that random profit in that period is given by $\tilde{\pi}_t^m$. It follows that

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[5] We thus make the simplifying assumption that the date of entry by a competitor is known. It is not clear that a model that treats the date of entry as uncertain would generate more insight so long as the key elements of our basic model, such as the fact that duopoly profit is lower than monopoly profit, are present. For instance, such a model may be set up by assuming that the entry date is a random variable and that λ_t is the earliest date at which a competitor can potentially catch up (that is, the lower bound of the support of a distribution of entry dates from the point of view of the licensee). We conjecture that our main results would continue to hold in this model, since the licensee's incentives to terminate or commercialize in a given period are guided by similar tradeoffs in both models.

cumulative profit at date $t \leq L$ is given by

$$\tilde{\Pi}_t = \tilde{\pi}_t^m + \sum_{n=t+1}^{\lambda_t - 1} \delta^{n-t} \pi_n^m + \sum_{n=\lambda_t}^{\infty} \delta^{n-t} \pi_n^d.$$

Denote the expected value of $\tilde{\Pi}_t$ by Π_t, that is $E[\tilde{\Pi}_t] = \Pi_t$. To simplify the characterization of the optimal commercialization rule, we make the following assumption.

Assumption 2. In every period t before the patent expires, the expected value from beginning to sell in period t is greater than the expected value from delaying commercialization to a later period.[6]

It is important to note that this assumption does not rule out the firm delaying commercialization for one period if realized profit turns out to be low in period t. Assumption 2 holds trivially if the profit distributions are constant over time and lead time, $\lambda_t - t$, is equal to a constant, representing a situation in which a certain and fixed amount of time is required before competitors can catch up with the innovator in the product market. This would be the case, for instance, if the uncertainty was caused by i.i.d. transitory shocks to either demand or production costs.

We now characterize the optimal decision rule for the general case. Suppose the licensee was successful in or before period $t \leq L$, but has not sold yet by date t. Under Assumption 2, it is straightforward to show that the licensee's optimal decision is to sell in period t if and only if

$$\tilde{\Pi}_t \geq \Pi_{t+1}. \tag{3}$$

The above decision rule implies that if the entry time is independent of the licensee's date of first sale, that is $\lambda_{t+1} = \lambda_t$, the licensee will sell in period t if and only if monopoly profit is non-negative in that period. More interestingly, straightforward calculations show that if $\lambda_{t+1} > \lambda_t$, (3) is equivalent to

$$\tilde{\pi}_t^m \geq \delta^{\lambda_t - t} \left[\sum_{s=0}^{\lambda_{t+1} - 1 - \lambda_t} \delta^s (\pi_{\lambda_{t+s}}^m - \pi_{\lambda_t + s}^d) \right] \equiv \Gamma_t. \tag{4}$$

Equation (4) has an intuitive interpretation. The optimal commercialization decision is guided by a tradeoff between selling for one more period and delaying commercialization

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[6] The results would continue to hold if Assumption 2 were relaxed, although the exposition would be lengthier.

and thus, imitation. Selling in period t will generate profit equal to $\tilde{\pi}_t^m$ in the period of first sale, while the discounted net benefit from delaying is represented by Γ_t.[7] The cutoff value for profit given by Γ_t depends on three crucial factors. One is $\lambda_t - t$, the licensee's lead time if the invention is commercialized in period t. The second factor is $\lambda_{t+1} - \lambda_t$, the amount of time by which the follower's entry will be pushed back if the licensee delays commercialization for one period. The third factor is the difference between expected monopoly and duopoly profit, $\pi^m_{\lambda_{t+s}} - \pi^d_{\lambda_t+s}$.[8]

Through its effect on the cost of imitation, the effectiveness of appropriability mechanisms used by the licensee will clearly affect the entry dates, λ_t and λ_{t+1}, and thus, the critical value for the net benefit from delaying. However, even with the intuitive assumption that more effective appropriability mechanisms lead to later entry and thus, higher values for λ_t and λ_{t+1}, in general, the relationship between the threshold in (4) and appropriability mechanisms is ambiguous and somewhat difficult to characterize. In the Appendix, we outline a model of the follower's imitation decision in which a higher marginal cost of imitation results in a higher optimal value for λ_t, the follower's entry date. The relationship between the marginal cost of imitation and a change in the difference $\lambda_{t+1} - \lambda_t$ is ambiguous because of its strong dependence on the sequence of per-period profit the follower expects to receive from λ_t on out. The sequence of per-period profit depends in turn on the stage of the product life cycle in which the licensee introduced the new product.

2.2 Likelihood of termination and commercialization

To complete our characterization of the value of the project given by (1), note that when Assumption 2 holds, V_t, the expected value from commercializing in period t before the licensee learns the realization of $\tilde{\pi}_t^m$, is simply equal to Π_t.[9] In other words, based on expected profit, the licensee would optimally commercialize immediately after technical success. However, as we have shown, it may end up delaying if, actual, realized profit in period t turns out to be less than expected.

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[7] Observe that Γ_t is strictly greater than zero whenever the following inequalities are satisfied: $\lambda_t > t$, $\lambda_{t+1} > \lambda_t$ and $\pi_t^m > \pi_t^d$.

[8] With (4), our model provides a formal basis for Lilien and Yoon's (1990) intuitive result stated in their Proposition 4.

[9] The option value from making an optimal commercialization decision in period t is equal to $V(\tilde{\pi}_t^m, t) = \max\{\tilde{\Pi}_t, EV(\pi_{t+1}^m, t+1)\}$. Hence, if Assumption 2 holds, $V_t \equiv EV(\tilde{\pi}_t^m, t) = \max\{E\tilde{\Pi}_t, EV(\pi_{t+1}^m, t+1)\} = \Pi_t$.

Based on the above analysis, the hazard of termination in period $t \leq \overline{L}$, that is, the probability of termination conditional on the licensee not having terminated or commercialized prior to t, is given by $\Pr(\tilde{\epsilon}_t \geq \Delta_t)$ or

$$H_d(t) = 1 - G(\Delta_t).$$

By Assumption 1, for $t > \overline{L}$, the hazard of termination is equal to one.

The hazard of commercialization in period $t \leq L$, that is, the probability of commercialization conditional on the licensee being successful before period t and it not having terminated or commercialized prior to t, is equal to $\Pr(\tilde{\pi}_t^m \geq \Gamma_t)$ or

$$H_f(t) = 1 - F_t^m(\Gamma_t).$$

To derive testable implications, we adopt the view that empirically available measures of appropriability provide information about the extent to which the licensee is able to obtain monopoly profits from commercializing a product based on the innovation. We also appeal to the constant lead time assumption under which Assumption 2 always holds, and we continue to assume that if the follower does not enter before the patent expires, it enters at the patent's expiration date. With these assumptions, expected values of profit are constant and $\lambda_t \equiv \min\{t + l^*, L\}$, where l^* is a positive constant.[10] In this case, if $\lambda_t < L$,

$$\Gamma_t = \delta^{l^*}(\pi^m - \pi^d) > 0,$$

and if $\lambda_t = \lambda_{t+1} = L$, then

$$\Gamma_t = 0.$$

The propositions below are stated without proofs because the results follow from a simple inspection of the expressions for Δ_t and Γ_t. The first proposition identifies the effect of key parameters on the hazard of termination and the second proposition provides results for the hazard of commercialization.[11]

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[10] Strictly speaking, lead time is only a constant if the patent's expiration date is far enough in the future. For patents with a short remaining statutory life, lead time is given by $L - t$ and is thus decreasing with time.

[11] Note that the hazard of termination depends on the monopoly and duopoly profit levels, while as illustrated by equation (4), the hazard of commercialization depends on the difference between expected monopoly and duopoly profits. Intuitively, the decision to terminate is based on the expected value of cumulative profit from successful commercialization and thus, on the expected profit levels in periods of sales. On the other hand, the decision to commercialize is motivated in part by the possibility of delaying sales to earn monopoly rather than duopoly profit in some periods. Hence, it naturally depends on the difference between these two expected profit levels.

Proposition 1 *Suppose that both the monopoly and the duopoly profit distributions are constant and that* $\lambda_t \equiv \min\{t+l^*, L\}$. *Then, other things equal, in every period for which the expected value from continuing to invest is positive* ($t < \overline{L}$) *and for which* $\lambda_t < \lambda_{t+1}$ *holds, the hazard of termination is decreasing in* l^*, π^m, π^d, δ, *and* q_t. *If in period* t, $\lambda_t = \lambda_{t+1} = L$, *the hazard of termination does not depend on* l^*. *Moreover, for* $t \geq \overline{L}$, *the hazard of termination is equal to one.*

Similarly, the following results hold for the hazard of commercialization.

Proposition 2 *Suppose that both the monopoly and the duopoly profit distributions are constant and that* $\lambda_t \equiv \min\{t + l^*, L\}$. *Then, other things equal, in every period prior to the patent's expiration date* ($t < L$) *for which* $\lambda_t < \lambda_{t+1}$ *holds, the hazard of commercialization is increasing in* l^* *and* δ *and it is decreasing in* $\pi^m - \pi^d$. *Moreover, if in period* t, $\lambda_t = \lambda_{t+1} = L$, *then the hazard of commercialization does not depend on* l^*, δ *or* $\pi^m - \pi^d$.

These results provide testable implications regarding the relationship between the hazards of termination and commercialization and variables that are directly affected by the licensee's ability to appropriate the returns from the innovation (l^*, π^m, π^d and $\pi^m - \pi^d$). Other variables such as δ and q_t may not directly relate to appropriability, but are reflective of specific characteristics of the firm and the licensed invention.

For patents with sufficiently long remaining statutory lives, the time window during which the licensee is able to appropriate most of the returns from the invention lasts l^* periods. The size of this window is clearly determined by the difficulty of non-infringing imitation. Following Mansfield (1986), Mansfield et al. (1981) and the simple model outlined in the Appendix, a stronger and broader patent as well as increased secrecy should intuitively result in an increased value for l^*.

Regarding specific firm characteristics, a large (and growing) number of firms that license university inventions are start-ups. To the extent that start-ups have less valuable outside options than larger well-established firms, they may be more patient as represented by a higher discount factor. Finally, it seems reasonable to expect that the probability of technical success is higher for inventions that were directly funded by the industry.

In the next section, we discuss the robustness of the results in Propositions 1 and 2 to relaxing the constant lead time assumption.

2.3 Relaxing the constant lead time assumption

Although similar results to those summarized in Proposition 1 also hold if we relax the constant lead time assumption, a complete analysis of the effect of relaxing this assumption on the follower's optimal entry date and the hazard of commercialization is tedious. Nonetheless, a discussion is in order as relaxing the assumption allows us to consider the role of expected profit dynamics. Such effects may be important if, for instance, a learning curve exists for the licensee, in the sense that the longer it has been in the market, the higher the duopoly profit the licensee is able to command when faced with competition (because of decreasing production costs or increasing product quality over time). With this interpretation, in (4), the existence of a learning curve implies that $\pi^d_{\lambda_t+s}$ increases as s increases. Of course, a larger share of industry profit for the licensee will lead to a smaller share for the imitating follower and thus, decreased incentives to follow soon after the licensee's date of first sale. The existence of learning effects will thus lead to both later imitation (an increase in λ_t) and a smaller difference between monopoly and duopoly profit (a decrease in the summation term in the expression for Γ_t). Since, holding $\lambda_{t+1} - \lambda_t$ constant, these two effects result in a lower value for Γ_t, they both contribute to an increased hazard of commercialization. Finally, any factors that lead to a lower value for duopoly profit, $\pi^d_{\lambda_t+s}$, will, ceteris paribus, increase the difference between monopoly and duopoly profits. This, in turn, will make lead time more important and reinforce the lower hazard of commercialization predicted by Proposition 2.

3 Empirical Method

The theory models the empirical reality in which attempts to commercialize patented inventions are either successful (in which case we may or may not observe a first sale) or not (in which case the license may be terminated or the licensee may continue development). The appropriate empirical specification for testing this theory is a competing risks model which adjusts for right censoring and the discrete nature of the data.[12]

Let T_f be the duration of a patent that is licensed until first sale and T_d be the duration of a license until it is terminated. Define $T = \min(T_f, T_d)$ and let d_f be an indicator which equals 1 if a patent is commercialized (first sale) from a license and 0

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[12] For detailed descriptions of competing risks models see Kalbfleisch and Prentice (1980) and Lancaster (1990).

otherwise. Let d_d be an indicator which equals 1 if a patent is terminated from a license and 0 otherwise. Only (T, d_f, d_d) are observed. Because d_f and d_d are observed, exclusion restrictions are not necessary to uncover the latent survival functions, $S\left(k_f, k_d|x\right)$, if there is sufficient variation in the vector of regressors x (Abbring and van den Berg 2000, Han and Hausman, 1990). Since our data are discrete, we employ a grouped data approach (Han and Hausman, 1990). Our model follows McCall (1996).

The probability of a patent being terminated from a license conditional on no events occurring through period $k-1$ is:

$$\Pr(T_d = k|X, T > k-1) = 1 - \exp(-\theta_d \exp(\alpha_{dk} + \beta_d' x)), \tag{5}$$

where x is a set of exogenous (possibly) time-varying regressors. Similarly,

$$\Pr(T_f = k|X, T > k-1) = 1 - \exp(-\theta_f \exp(\alpha_{fk} + \beta_f' x)), \tag{6}$$

is the probability a first sale associated with a patent occurs conditional on no events occurring through period $k-1$. Period subscripts on x are dropped for readability. Because the theory does not provide us with guidance as to possible exclusion restrictions, we assume that regressors x are identical in both equations.

The joint survivor function conditional on x is:

$$S(k_s, k_d|x) = \exp\left(-\theta_f \sum_{r=1}^{k_f} \exp(\alpha_{fk} + \beta_f' x) - \theta_d \sum_{r=1}^{k_d} \exp(\alpha_{dk} + \beta_d' x)\right). \tag{7}$$

In what follows, let $\Theta = \{\theta_f, \theta_d\}$. α_{wk} are the baseline parameters and can be interpreted as:

$$\alpha_{wk} = \log\left(\int_{k-1}^{k} h_w(t)dt\right),$$

where $h_w(t)$ is the underlying baseline hazard function and $w \in \{f, d\}$. α_{dk} and α_{fk} are the respective baseline hazards and are assumed to follow a 3rd order polynomial. A 3rd order polynomial is sufficiently flexible to approximate a baseline hazard function of only five periods. Thus

$$\alpha_{wk} = \alpha_{0k} + \alpha_{1k}k + \alpha_{2k}k^2 + \alpha_{3k}k^3. \tag{8}$$

The vectors of parameters β_w represent the effects of the exogenous variables. Note that all covariates are constant except patent age and year. Define

$$P_f(k) \quad = \quad S(k-1, k-1|\Theta) - S(k, k-1|\Theta) - 0.5[S(k-1, k-1|\Theta) + S(k, k|\Theta)$$

$$
\begin{aligned}
&- \quad S(k-1,k|\Theta) - S(k,k-1)|\Theta],\\
P_d(k) \quad &= \quad S(k-1,k-1|\Theta) - S(k-1,k|\Theta) - 0.5[S(k-1,k-1|\Theta) + S(k,k|\Theta)\\
&- \quad S(k-1,k|\Theta) - S(k,k-1)|\Theta],\\
P_c(k) \quad &= \quad S(k-1,k-1|\Theta),
\end{aligned}
$$

where $P_f(k)$ is the unconditional probability of first sale by the beginning of period k, $P_d(k)$ is the unconditional probability of a patent being terminated from a license by the beginning of period k, and $P_c(k)$ is the unconditional probability of neither event occurring through the beginning of period k. An adjustment, $0.5[S(k-1,k-1|\Theta) + S(k,k|\Theta) - S(k-1,k|\Theta) - S(k,k-1|\Theta)]$ is made because durations are measured in discrete time.

A key problem with competing risks models identified in the literature is that when the risks are not allowed to correlate, a potential bias may arise. Unobserved determinants of one event (first sale) may be correlated with unobserved determinants of the complementary event (termination) and duration (decision to do neither). We might expect unobserved components, such as quality of the patent and uncertainty associated with success of the technology, to affect both decisions. In our specification, we allow risks to correlate by permitting a three mass-point distribution of location parameter pairs θ_{dj}, θ_{fj} where $j = 1, 2, 3$. Each pair occurs with probability p_j. The six location parameters and two free probabilities are estimated by the data. Thus,

$$\wp_w(k) = \sum_{j=1}^{3} p_j P_w(k|\Theta_j) \tag{9}$$

The log-likelihood is:

$$\log\ L = \sum_{n=1}^{N} \sum_{k=1}^{K_n} d_{fk}^n \log \wp_{fk}^n + d_{dk}^n \log \wp_{dk}^n + (1 - d_{fk}^n)(1 - d_{dk}^n) \log \wp_{ck}^n. \tag{10}$$

for each of the K_n periods of each of the N attempts.

To identify the model, the baseline hazards α_{f0} and α_{d0} are fixed to zero. As there is no constant in the regression, we use deviations from the means in x.

4 Data

The data used to test the model's predictions were collected from the Technology Licensing Office (TLO) at the Massachusetts Institute of Technology on patents assigned to the Institute between 1980 and 1996 and licensed to private sector firms. The data include all patented inventions by MIT faculty, staff and students from 1980 through 1996 that were assigned to the Institute and licensed to at least one private firm.

Our data set is an unbalanced, right censored panel. We have yearly data for each attempt from the date of the contractual agreement on the patent until one of the three events occurs: it is right censored (in 1996), it is terminated or it is commercialized. An observation begins the year that MIT TLO records indicate that a firm first licensed a patent. We code TERMINATION as zero, except in the year (if any) that MIT TLO records indicate that the licensing agreement by the given firm no longer covered the invention or if the patent expired, thereby negating the license. We code FIRSTSALE as zero, except in the year (if any) that the MIT TLO records indicate that the first dollar of sales from a product or service embodying the invention was achieved.

There are 805 exclusive licenses corresponding to 2,875 periods in which licenses were at risk. While it is plausible that licenses are terminated after commercialization, the MIT TLO reports that this is a rare event, and hence this information was not collected. That is, we only observe the first event that occurs. The analysis below predicts the likelihood of the first event.[13]

Table 1 reports the summary statistics. Note that patent age reflects the mean age of patents at the time of license. Table 2 reports the unconditional survival rates and the extent of right censoring in the sample. First and foremost, firms are far more likely to terminate licenses of patents than to successfully commercialize them (323 terminations vs. 197 successes). The table also suggests that uncertainty associated with an innovation is generally resolved in the first 5 years of license because 85% of licenses either lead to commercialization or are terminated by the end of period 5, and 90% of the observed events occur in the first five periods. (We observe only 2 events after period 10.) The sparseness of this right tail implies that there is little information on which to estimate a baseline hazard. Therefore, we recoded all observations that survived more than five periods as right censored after five periods. The majority (257) are censored during the first four years of the license due to the closing of our observation window in 1996. In addition to the observations that are right-censored after 1996, we censored an additional 74 observations.[14]

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[13] Coding of commercialization was straightforward, as this is directly reported in the MIT data.

[14] There are three ways in which to interpret this censoring phenomenon. First, our model suggests right censoring reflects unresolved uncertainty surrounding the invention's commercial prospects. This is our interpretation. Second, it is possible that we are simply missing data. We can rule out this

As measures of importance of the appropriability mechanisms used in a line of business, we employ four measures from the Yale survey on innovation: patent strength, secrecy, lead time and learning (Levin et al., 1985; Levin et al., 1987). These measures are survey line of business averages derived from perceptions of 650 high-level R&D managers in 130 lines of business about central tendencies of the effectiveness of different mechanisms used to appropriate the returns to innovation for process or product R&D in their lines of business. The managers were asked to rate mechanisms on seven point Likert scales.[15] The items are constructed from responses to the following question posed both for production processes and products: "In this line of business, how effective is each of the following means of capturing and protecting the competitive advantages of new or improved products (production processes)". Respondents answered on a seven point Likert scale from "not at all effective" to "very effective".

Patent strength is a measure of the effectiveness of patents as a way to capture and protect competitive advantage in a line of business. It is created from the average response for production processes and products for two means of appropriability: "patents to prevent competitors from duplicating the product (process)" and "patents to secure royalty income". Secrecy is a measure of the effectiveness of keeping key information secret as a way to capture and protect competitive advantage in a line of business. It is created from the average response for production processes and products to "secrecy" as a means of capturing and protecting the competitive advantages of new or improved production processes (products). Lead time is a measure of the effectiveness of being an early mover as a way to capture and protect competitive advantage in a line of business. It is created from the average response for production processes and products to "lead

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possibility due to the nature of MIT's record keeping, which is comprehensive given the financial value of those records. Third, it is possible that delays are cases in which licensees are "sitting" on the patent as a mechanism to keep competitors from exploiting the technology. While we are unable to refute this possibility out of hand, we view it as unlikely. Licensing contracts at MIT commonly give the Institute march-in rights for this specific eventuality which can be triggered if there is no evidence of progress by a licensee. Moreover, licensing fees are generally required on an annual basis. Thus, a firm incurs a real cost if it chooses to sit on a patent.

[15] To ensure the reliability and validity of their survey, the scholars who conducted the Yale survey pretested their survey with managers from diverse businesses. In addition, to mitigate intra-industry heterogeneity, the respondents were asked to identify major innovations in their industry, and there was not significant variation in responses to this question within industries. Because of their reliability and validity, the measures have been used in several subsequent studies (Cohen and Levinthal 1990, Levin et al., 1985).

time (being first with a new process [product])". Learning is a measure of the effectiveness of moving ahead of competitors on the learning curve as a way to capture and protect the competitive advantages in a line of business. It is created from the average response for production processes and products to "moving quickly down the learning curve".

Because our sample covers the years 1980-1996, while the survey measures appropriability conditions at a particular point in time, we must assume that the appropriability differences between lines of business are relatively stable throughout our observation period. There is some evidence that cross-industry differences in such factors in appropriability do not vary significantly over time, as they are a function of the underlying technology in a line of business (Cohen and Levin 1989). Although one might argue that the relative strength of patents increased during the period, the intellectual property protection afforded by patents for, say, chemical compounds remains very strong relative to that for electronic devices.

We also employ Lerner's (1994) measure of PATENT SCOPE, which is based upon the number of international patent classifications found on the patent. Lerner (1994) finds that this measure is associated with various measures of economic importance: firm valuation, likelihood of patent litigation, and citations. He argues that it represents broader scope of the monopoly rights covered by the patents. In contrast to the Yale measures, this variable is patent specific.[16]

The fact that we do not observe many licenses extending beyond 5 years without a commercialization or termination event does not imply that uncertainty is resolved within five years of issuance of a patent. It is common for licenses to survive well into patent life before first sale or termination (Table 3). The variation in patent age at the time of license allows us to separately control for the effects of the age of the license and the age of the patent on the hazards of first sale and termination. The former are measured by the baseline hazard estimates, while the latter are measured by the coefficients on age. We measure AGE OF PATENT as the number of years since the patent was issued, conditional on patent issue at time of license.

We also include TECHNOLOGY CLASS dummies. Following the Hall, Jaffe, and

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[16] The writing of a patent can be part of a legal strategy as well as an administrative task. If, for example, narrower patents were to issue more quickly, then firms would have an incentive not to bargain over classifications with the patent examiner. Hence, the patent scope measure may, in some circumstances, be endogenous to patent quality. While we know of little systematic research that addresses this point, it suggests that we should interpret measurable effects of this variable cautiously.

Trajtenberg (2001) classification of patents, we break the patents into five categories: drugs, electronics (including computers and communications), chemicals, mechanical, and other because we might expect different types of technology to take longer to reach first sale, as is the case for drugs, which need to first obtain FDA approval. [17] Unfortunately, we could not include finer grade industry controls such as three-digit US patent class dummies because the appropriability measures are associated with lines of business, which are, in turn, mapped to the patents via their primary three-digit US patent classes. Hence, there is no variation in the Yale appropriability measures within three-digit patent classes.

For patent classes in which there are a sufficiently high number of observations, we can include patent class dummies. Our data span 108 patent classes, 86 of which perfectly predict outcomes because they are represented in the data by one or two patents. We estimate a variant of Model 4g, using 24 patent classes as controls and pooling the remainder. The results of this regression (available upon request) were almost identical to those that appear in Model 4g. Given the limits of our data, we were unable to estimate a model that simultaneously accounted for unobserved heterogeneity and included these patent class controls. Nevertheless, our results should be interpreted as reflecting an association between appropriability conditions in line of business and termination and commercialization hazards. To the extent that such an association might be associated with other unobserved factors, our results must be qualified.

Finally, we also include a dummy variable that takes the value 1 if the patent was licensed to a startup, defined as a firm formed to license the particular technology. (33% of the patents in our sample were licensed to startups). We also include a dummy variable that indicates whether the research the led to the patented invention was funded by industry. (16.8% of the patents were the result of industry funded research). Industry funding does not, however, imply that the firm that funded the research necessarily was the licensee. While research sponsors are not generally afforded special licensing rights, in practice we might expect them to be aware of research results earlier than non-sponsors. (We are unable to identify cases in which sponsors licensed output of research they funded because we do not observe the identity of the research sponsors).

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[17] Reduced form hazard ratios suggest that event patterns in the various categories are distinct. For example, licenses of drug patents tend to survive longer than other types of inventions. Unfortunately, the data do not allow us to econometrically distinguish these differences.

5 Empirical Results

Our central results can be found in Table 4, Model a.[18] The results control for unobserved heterogeneity non-parametrically as per the method described above, for the broad technology class (the omitted class is chemical patents), patent age and technology vintage. In addition, we include dummies for whether the firm was a startup as well as whether or not the research that led to the patent was sponsored by industry.[19]

Following our interpretation of PATENT STRENGTH, PATENT SCOPE and SECRECY as increasing the cost and therefore the time to imitation, we expect each of these variables to be negatively associated with the hazard of termination (Proposition 1). We find that the coefficients on PATENT STRENGTH and SECRECY are both negative and significant in the termination equation. The PATENT SCOPE coefficient point estimate is negative, although not significant.

To get a sense of the magnitude of the effects, and following the literature of these types of competing risks models, we compute the change in the predicted probabilities of events for the sample. Because the Yale Survey measures are derived from a Likert scale,

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[18] Our unit of observation is a patent. In university licensing, several patents may be licensed in a single agreement. If there are many such cases, and they reflect instances in which a single technology is protected through multiple patents, our regressions would overweight these technologies. If such technologies are systematically different than those licensed through single patents, then this pattern would introduce bias into our analysis. This problem is mitigated by allowing the error terms to be correlated within each agreement. Unfortunately, we are not aware of a method to implement this strategy and simultaneously control for unobserved heterogeneity. Because we believe that unobserved heterogeneity is a greater problem than the overweighting of technologies represented by a single patent, we choose to control for unobserved heterogeneity in our analyses. (It is important to note that we do not average patent characteristics within a license because this would create a problem as large as the one it would solve. Averaging would leave us unable to accommodate the cases in which one of the licensed patents were either commercialized or terminated separately from the rest of the patents under the license agreement, which we observe in a significant number of cases. Moreover, discussions with the director of the MIT Technology Licensing Office indicates that separate termination is a common occurrence and is represented by several anecdotes in the "lay" theory of technology transfer officers about how to think about these data.)

[19] It is interesting to note that the unobserved components seem to be positively correlated. We find this result weakly in all models we estimated with unobserved heterogeneity. Interpretation of this result depends on what we believe is unobserved. For example, if we are picking up unobserved quality, then we would think of θ_{11}, θ_{12}, and θ_{13} as picking up high-quality patents, and θ_{21}, θ_{22}, θ_{23} as picking up low quality patents. In this case the model predicts much lower hazards of events with high quality patents than low quality patents.

we look at effect of a change in one standard deviation from the mean on the predicted probability of events for the sample. Model 4c predicts both the mean probability of termination and commercialization for the sample to be 0.12. If each manager in a line of business associated with each of the inventions had rated the effectiveness of patents one standard deviation higher, the probability of termination for the sample patents would decrease to 0.098, or 17.5%. Similarly, if each manager had rated secrecy one standard deviation higher, the predicted probability of termination decreases to 0.1, or 16%.

Following our interpretation of LEARNING and LEAD TIME, we expect a high value of LEARNING to increase π^d, and a high value of LEADTIME to reduce π^d. Therefore, Propostion 1 implies that LEAD TIME is positively related to the hazard of termination, and LEARNING is negatively related to it. We find that, although point estimate for LEAD TIME is positive, it is not significant across specifications. LEARNING is consistently negatively related to termination hazards, but we are unable to measure this effect with precision.

Proposition 2 predicts that the hazard of commercialization will increase with increases in PATENT STRENGTH, PATENT SCOPE and SECRECY. While we consistently measure positive coefficients for each of these independent variables, only PATENT SCOPE is measured with precision. We find that each additional international patent class associated with the patent increases the mean predicted probability of commercialization for the sample to 0.14, which represents an increase of 16.5%. In the model, we follow Mansfield et al. (1981), who consider that greater patent scope increases imitation costs. With this interpretation, the effect of patent scope on the probability of commercialization should be no different from that of patent strength or secrecy. However, under the alternative interpretation that patent scope increases the probability that a profitable market for the licensed technology exists, then better patent scope will cause a shift in F^m, the distribution of monopoly profit outcomes. Other things constant, a decrease in F^m (a probability shift towards higher realizations) increases the hazard of commercialization. This interpretation, which relies on mechanisms that differ from those associated with patent strength or secrecy, may explain the discrepancy in the empirical findings for these three appropriability measures.

Since we associate the importance of LEARNING with a high π^d and the importance of LEAD TIME with a low π^d, Proposition 2 predicts that LEARNING will be positively associated with the hazard of commercialization, while LEAD TIME will be negatively related to that hazard. We do find that LEAD TIME is significantly associated with a decrease in the hazard of commercialization. A one standard deviation change in LEAD TIME is associated with a reduction in the commercialization probability from 0.12 to 0.09, a 21% decline.

In contrast to our finding for LEADTIME, a one standard deviation increase in the importance of LEARNING increases the probability of commercialization by 20% (the mean predicted probability increases from 0.12 to 0.14).[20]

We investigate the robustness of these results to specification in Models b-g which are reported in Table 4.[21] In Model 4b, we remove dummy variables for STARTUP and INDUSTRY FUNDED. The results are qualitatively similar to Model 4a, although the coefficient on LEAD TIME now has a significant impact on termination. We see in Model 4c that this result is sensitive to the inclusion of the INDUSTRY FUNDED dummy, which suggests that the result in Model 4b is not due to LEAD TIME per se, but rather the fact that high LEAD TIME inventions tend not to be INDUSTRY FUNDED.

In Models 4d, 4e and 4f, we further evaluate the sensitivity of the results by removing class controls, age controls, and vintage controls consecutively. We find that the our results are robust to the exclusion of class controls in Model 4d.[22] In Model 4e, we find that the results are robust to the exclusion of the patent age variable (which picks up information on the remaining life of the patent). In Model 4f, year controls are omitted. Qualitatively, the results are unchanged.[23]

In Model 4g, we restrict the risks to be independent, and do not allow unobserved heterogeneity. We strongly reject the hypothesis that there is no unobserved heterogeneity and independent risks (LR statistic = 116.24). While the sign of each coefficient does

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[20] Moreover, as argued in Section 2.3, the effect of learning would be compounded if the time to imitation were endogenized because it would enhance duopoly profits for the first entrant (i.e., the licensee).

[21] To investigate the robustness of the results with respect to method, we also ran Cox proportional hazards models, which cannot account for competing risks. These regressions gave stronger results.

[22] Beyond exclusivity, we do not observe the licensing terms of the patents. It is possible that differences in royalty terms might explain outcomes, and that royalty terms might be correlated with independent variables of interest. Our conversations with TLO staff at MIT suggest that there is not huge variation in royalty terms across licenses, that where there is variation, it is primarily across broad patent classes. Hence, the lack of royalty terms in our regression equations might lead to an overstatement of the effects of these controls.

[23] It was not possible to estimate a model with the exclusion of class, age, and year controls that also includes a 3-point mass structure, or a cubic form for the baseline hazard due to convergence problems. We suspect that this model is not properly identified due to insufficient variation in the data (see Abbring and van den Berg 2000).

not change, the variables PATENT STRENGTH, LEARNING, and LEAD TIME are no longer significant predictors of commercialization. Compared to Model 4a, LEARNING now negatively predicts termination, whereas STARTUP does not.[24] Thus, the data suggest that unobserved heterogeneity is an important characteristic of our data. Failing to control for this obfuscates our central results.

To understand the intuition behind this result, consider that, in Model 4a we found that the hazard of termination decreases if the technology is licensed to a STARTUP, but the hazard of commercialization does not. By contrast, in Model 4g, we find no effect. The sensitivity of the result for STARTUP to controlling for unobserved heterogeneity is what one might expect if start-ups not only differ from well-established firms, but also license inventions that are different from those licensed by established firms. For example, if startups license earlier and riskier inventions, as represented by a relatively lower probability of success q_t, but have higher discount factors δ and are more reluctant to terminate the license (because terminating the license agreements might imply terminating the startups as well), then these two effects would tend to cancel out. However, after controlling for this heterogeneity, then Model 4a shows that startup firms are more likely than other licensees to terminate the development projects.

From our robustness analysis, we conclude that, as predicted by the theoretical model, the hazard of termination is decreasing in PATENT STRENGTH and SECRECY. The hazard of commercialization is decreasing in LEAD TIME, and increasing in LEARNING and PATENT SCOPE.

6 Conclusion

We investigate the role of patents and other appropriability mechanisms in the commercialization of university inventions. An important characteristic of these inventions is that they typically require further development, which is risky for both technical and market reasons. Thus, our theory considers the problem faced by a firm that must decide in each period whether to invest in further development of an invention it has licensed, or to terminate the project. If technical development is successful, the firm then decides when to commercialize. The optimal timing of commercialization depends on a tradeoff between quick market introduction and the size of profits in the first period of sales. We

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[24] If we interpret start-ups as having higher discount factors, then the theoretical model predicts that start-ups will be less likely to terminate their license agreements.

derive comparative statics results based on a variety of appropriability measures, which provide a set of hypotheses. We test the hypotheses by applying a competing risks hazard model that allows for correlated risks and non-parametric unobserved heterogeneity to a dataset of 805 licenses of MIT patents.

Both the theoretical and empirical analysis suggest that the hazard of terminating a license is decreasing in the effectiveness of patent strength and secrecy. By contrast, while the theory predicts that the hazard of commercialization is increasing in both measures, we find no statistically significant relationship.

The theoretical model also explores a somewhat counter-intuitive effect that when lead time is important, it may be optimal for firms to delay commercialization until demand is favorable in order to obtain the highest possible returns in periods of monopoly rents. Our empirical findings support this prediction. In addition, both theoretically and empirically, patent scope and learning have a positive effect on the hazard of commercialization. These results suggest that, when profiting from these inventions relies heavily on learning, firms should commercialize them as soon as is technically feasible. By contrast, when lead time is important, firms may well do better by waiting for the best opportunity to introduce a product into the market.

A few caveats are in order. First, both the theoretical and empirical analysis presume that firms licensing these inventions intend to commercialize them. While we believe this is a fair assumption given the laws and university policies governing university licensing, it is possible that university attempts to prevent firms from shelving are not perfect. If milestones or annual fees are sufficiently low, it may be profitable for firms to maintain their licenses, preventing competitors from having access to the inventions (as would be the case if the inventions were returned to MIT). While we cannot eliminate this possibility, recent evidence suggests that typical university licensing contract terms are designed to guard against this occurrence (Thursby et al. 2005).

Second, note that we have presumed that termination results when the firm decides not to continue developing a commercial product. However, if the property rights are weak, as we might expect in, say, electronics or mechanical engineering inventions, a firm may maintain a license until critical, but non-protectable knowledge is transferred, and then drop the license and invent around the invention.[25] Hence, a result of a terminated patent (license) is not necessarily indicative of lack of technology transfer, or of a

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[25] Katharine Ku, head of the Stanford Office of Technology Licensing has indicated to the authors that not only does this happen, but it is considered fair-play and not at all unethical.

technology failure (Goldfarb and Henrekson, 2003).

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Table 1: Descriptive Statistics

Variable	**Mean**	**Std. Dev.**	**Min.**	**Max.**
Lead Time	5.369	0.506	4	6.13
Secrecy	3.923	0.406	3	4.88
Learning	5.003	0.435	4	5.75
Patent Strength	4.108	0.747	1.75	5.32
Patent Scope	1.339	0.639	1	6
Start-up	0.327	0.469	0	1
Industry Funded	0.168	0.374	0	1
Drug Patent	0.216	0.412	0	1
Chemical Patent	0.311	0.463	0	1
Electric Patent	0.265	0.441	0	1
Mechanical Patent	0.032	0.177	0	1
Other Technology	0.176	0.381	0	1
Patent Age (years since application)	2.985	3.122	0	16
Patent Age Squared	18.637	33.596	0	256
N		805		

Table 2: Termination, commercialization and right censoring by age of license

Age of License	**Termination**	**Commercialization**	**Right Censored**	**Total**
1	74	49	79	805
2	32	26	48	604
3	54	40	98	497
4	49	20	35	305
5	34	11	34	201
6	8	2	10	122
7	10	6	11	103
8	6	2	9	76
9	0	11	8	59
10	1	0	15	39
11	1	1	7	24
12	0	0	2	15
13	0	0	8	13
14	0	0	2	6
15	0	0	2	4
16	0	0	2	2
Total	269	168	370	2875

Table 3: Termination, commercialization and right censoring by patent age

Patent Age	**Termination**	**First Sale**	**Right Censored**	**Total**
0	38	9	2	48
1	38	25	49	112
2	31	15	30	76
3	24	14	36	74
4	37	21	28	85
5	20	8	40	68
6	12	14	26	52
7	15	16	38	69
8	13	14	25	52
9	11	12	21	44
10	12	5	19	36
11	7	7	5	19
12	8	5	4	17
13	3	0	9	12
14	0	1	7	8
15	0	2	15	17
16	0	0	14	14
17	0	0	2	2
Tot	269	168	370	805

Figure 1: Unconditional event hazards by period

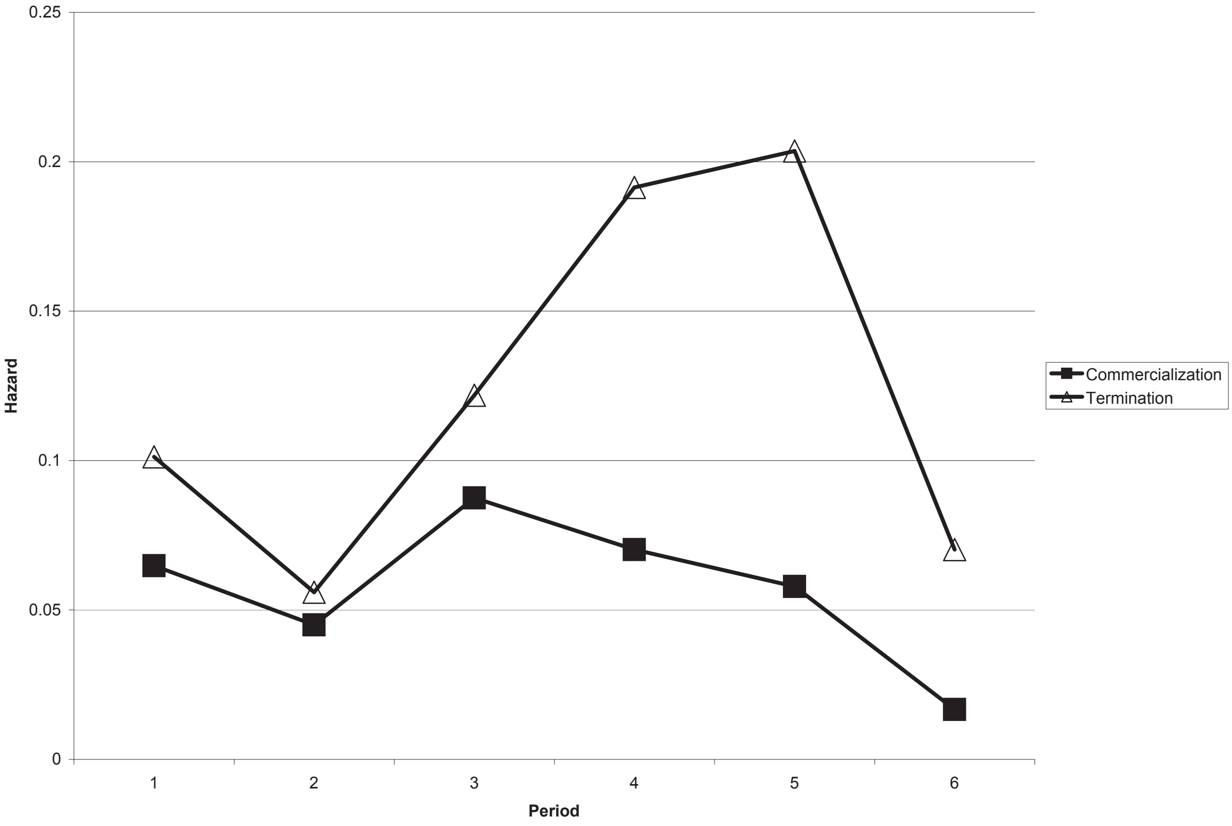

Table 4: Hazard Regressions

Method	Correlated risks with unobserved heterogeneity												Independent Risks	
	a		b		c		d		e		f		g	
	Dependent Variable													
	Termination	Commercialization	Termination	Commerclizationn	Termination	Commercializationn	Termination	Commercialization	Termination	Commercialization	Termination	Commercialization	Termination	Commercialization
LEAD TIME	0.099	-2.018**	1.145*	-1.445*	0.793	-1.612*	0.846*	-1.420**	1.067**	-0.940*	0.758*	-1.258**	0.859**	-0.322
	0.442	0.672	0.480	0.595	0.456	0.612	0.374	0.495	0.393	0.436	0.369	0.393	0.272	0.367
SECRECY	-1.607**	1.431	-1.368**	1.3587	-1.271*	1.290	-1.057**	0.672	-1.030*	0.594	-0.878*	0.561	-0.913**	0.244
	0.431	0.826	0.474	0.701	0.450	0.710	0.396	0.587	0.410	0.597	0.385	0.449	0.257	0.427
LEARNING	0.476	3.828**	-0.628	3.331**	-0.313	3.524**	-0.381	3.506**	-0.564	2.910**	-0.132	2.414**	-0.744*	0.799
	0.493	1.114	0.481	0.970	0.466	1.038	0.379	0.899	0.371	0.776	0.396	0.592	0.302	0.509
PATENT	-1.066**	0.859	-1.189**	0.702	-1.105**	0.652	-1.145**	0.328	-1.379**	0.341	-1.179**	0.634	-0.666**	0.515
STRENGTH	0.330	0.621	0.336	0.496	0.331	0.503	0.212	0.421	0.223	0.384	0.202	0.343	0.192	0.305
PATENT	-0.238	0.718**	-0.171	0.635*	-0.111	0.658*	-0.113	0.691**	-0.132	0.564**	0.047	0.584**	-0.127	0.247
SCOPE	0.209	0.252	0.196	0.261	0.196	0.253	0.183	0.208	0.189	0.181	0.169	0.175	0.129	0.137
STARTUP	-1.090**	0.331											0.043	0.057
	0.251	0.415											0.172	0.209
INDUSTRY	-0.873**	-0.435			-0.678**	-0.425							-0.507*	0.335
FUNDED	0.316	0.516			0.331	0.504							0.223	0.274
DRUGS	-0.153	-1.054	-0.536	-1.002	-0.359	-0.947							-0.083	-0.739
	0.652	0.801	0.693	0.788	0.688	0.790							0.372	0.463
ELEC	-0.240	0.462	-0.126	0.161	-0.092	0.260							-0.341	-0.089
	0.402	0.645	0.370	0.579	0.361	0.607							0.231	0.314
MECH	-0.377	-4.048*	-0.402	-4.433*	-0.245	-4.321*							-0.192	-1.023
	0.486	1.671	0.520	1.680	0.493	1.550							0.362	0.754
OTHER	-0.421	-1.696*	0.032	-1.814*	-0.194	-1.891*							-0.102	-0.718*
	0.420	0.686	0.418	0.661	0.409	0.671							0.258	0.332
AGE	-0.258*	0.654**	-0.247*	0.678**	-0.251**	0.677**	-0.240*	0.502**					-0.289**	0.190
	0.107	0.205	0.113	0.198	0.111	0.200	0.102	0.172					0.078	0.108
AGESQ	0.013*	-0.035**	0.0125	-0.037**	0.012	-0.037**	0.012*	-0.029**					0.017**	-0.007
Year Dummies	Yes		Yes		Yes		Yes		Yes		No		Yes	
LL	-976.041		-986.515		-984.428		-999.549		-1007.840		-1113.881		-1022.560	

7 The imitator's problem

In the main text, we take the behavior of a potential competitor as given and made assumptions on how the entry date varies with the innovating firm's date of first sale. We now show that this relationship arises endogenously in a simple model of entry decision by an imitator. Suppose that another firm, the follower, invests in developing a non-infringing substitute to the licensed technology as soon as the innovating firm has commercialized in period t. Let w be a parameter representing the scope of the patent on the licensed technology and μ be the follower's discount rate. We assume that to be able to enter the market in period $t+l$, and obtain expected profit of π_t^F per period, the total (discounted) cost of development to the imitating firm is given by $I(l,w)$. For a given w, $I(l,w)$ decreases with l to reflect the fact that the sooner the entry date, the higher the development cost (this is similar to Benoit, 1985). Also assume that there are decreasing returns to development investment in the sense that for a given w, $MC(l,w) \equiv I(l,w) - I(l+1,w)$, the marginal cost of imitating one period sooner, is higher the shorter the lag l. Of course, following Mansfield at al. (1981), this marginal cost of development over time is also higher, the higher w. Finally, for simplicity, we assume that $\sum_{z=L}^{\infty} \mu^{z-t}\pi_z^F - I(L-t,w) > 0$ for every $t \leq L$ and that the marginal cost of imitating one period earlier is equal to zero for periods greater than L. Hence, the follower enters on the patent's expiration date if it did not enter before.

In this model, in period t, total expected profit from entering at date $t+l$ is equal to

$$\Pi^F(t+l) = \mu^l \sum_{z=0}^{\infty} \mu^z \pi_{t+l+z}^F.$$

where, for simplicity, we assume $\pi_t^F = \pi^F$ for every $t > L$. Hence, profit net of development cost is equal to

$$\Pi^F(t+l) - I(l,w). \tag{11}$$

Suppose that there exists an $l \geq 1$ for which (11) is greater than the profit from waiting until the end of the patent's life.[26] Then, in general, for every t and l, the marginal benefit from entering one period sooner in period $t+l$ rather than in period $t+l+1$ is equal to

$$\delta^l \pi_{t+l}^F,$$

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[26] Otherwise, the imitator waits until the end of the patent's life to enter because it is not profitable to do so earlier.

while the marginal cost from doing so is equal to

$$I(l, w) - I(l+1, w).$$

Therefore, if the follower enters before the end of the patent's life, the optimal entry date, $t + l_t^*$, must satisfy the following marginal conditions

$$\mu^{l_t^*} \pi_{t+l_t^*}^F \geq MC(l_t^*, w),$$

and

$$\mu^{l_t^*-1} \pi_{t+l_t^*-1}^F < MC(l_t^* - 1, w).$$

If π_t^F is constant then these conditions are given by

$$\mu^{l_t^*} \pi^F \geq MC(l_t^*, w),$$

and

$$\mu^{l_t^*-1} \pi^F < MC(l_t^* - 1, w).$$

The solution clearly satisfies $l_t^* \equiv l^*$, that is, the time to successful imitation is independent of t. Hence, in this case, for a given date of first sale by the incumbent, the optimal entry time by the follower is given by $\lambda_t = \min\{t + l^*, L\}$.