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ABSTRACT

At least since Arrow (1962), economists have believed that strong property rights are necessary for firms to invest in innovation. This belief was a key principle underlying the Bayh-Dole Act, which gave universities the right to own and license federally funded inventions, because the commercialization of university inventions requires private firm investment in development, given the early stage of these inventions at the time that they are licensed. However, surprisingly little research has examined this key principle. In this paper, we exploit a database of 805 attempts by private firms to commercialize inventions licensed exclusively from MIT between 1980 and 1996 to address this issue. The data allow us to examine the timing of subsequent commercialization or termination of the licenses to these inventions as a function of the length of patent protection, as well as other measures of appropriability. We model the firm's investment decision as an optimal stopping problem, and we characterize the hazard rates of first sale and termination over time. In both the theory and the empirical analysis, we find two opposing effects of time. The length of patent protection provides an incentive for the firm to invest that declines with time; while the probability of technical success increases in each period that the firm invests. Competing risks models to predict the resulting hazards of first sale and termination reveal that, for these data, the hazard of first sale has an inverted u-shape and the hazard of termination has a u-shape. We find that increased appropriability, as measured by Lerner's index of patent scope and effectiveness of patents in a line of business, decrease the hazard of termination and increase the hazard of first sale.

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1 Introduction

University patent licensing has grown steadily in the two decades since the Bayh-Dole Act gave universities the right to own and license the results of federally funded research.[3] While many researchers and policy makers cite the passage of the Bayh-Dole Act as instrumental in facilitating the commercialization of university inventions, others question whether the Act has mattered at all. As a result, the debate over the value of giving universities the property rights to federally-funded inventions has continued since the initial discussion of the Act in the late 1970s and shows no sign of abating. In fact, within the last year, Congress, the National Academies' Committee on Science, Technology, and Economic Policy, and the President's Commission on Science and Technology have all undertaken review of Bayh-Dole.

Beneath the rhetoric, there has been surprisingly little analysis of the key principle underlying the debate: would private firms adopt and commercialize university inventions in the absence of strong property rights to the inventions results? Some observers say the answer is yes. As noted by Nelson (2001), two of the most important university patents (Cohen-Boyer at Stanford and Axel at Columbia) were adopted by companies without exclusive licenses. In their case-study analysis, Colyvas et al. (2002) find that inventions "ready for use" (four of their ten cases) were successfully licensed and put to commercial use without exclusive license. There is also extensive evidence of university research that has been transferred to industry by other means than technology licensing, including publications, consulting, and conference participation (See, for example, Adams, 1990; Agrawal and Henderson, 2002; Cohen et al., 1998; Jaffe, 1989; Mansfield, 1995; and Zucker et al., 1998).

Nonetheless, the proponents of Bayh-Dole argue that because the commercial success of university inventions is highly uncertain and typically requires substantial development, private firms will not make the necessary investment unless they can appropriate the returns to that investment. It has long been recognized that

[3] According to the Association of University Technology Managers (AUTM), the number of universities with technology transfer offices grew from 20 in 1980 to over 200 in 1990. For the 95 US institutions responding to the AUTM survey in both 1991 and 1999, the number of inventions disclosed by faculty increased 65% to a total of 8457 in 1997, the number of new patent applications filed increased 175% to 4032, the number of license and option agreements executed increased 135% to 2734, and royalties increased more than 250% (in real terms) to around $665 million.

uncertainty and inappropriability can lead to underinvestment in research and development (the classic reference being Arrow, 1962). University inventions are uncertain and require subsequent development to achieve commercial success. A recent survey of businesses who license from universities indicates that almost half of university inventions fail (Thursby and Thursby, 2003). Moreover, a survey of sixty-two U.S. university technology transfer offices provides evidence that eighty-eight percent of the inventions licensed require further development, and seventy-five percent are so embryonic that commercial success requires faculty participation in the process (Thursby et al., 2001). Jensen and Thursby (2001) construct a model of exclusive licensing and show that the necessary faculty participation would not be forthcoming without license payments tied to firm performance, such as royalties or equity. The focus of this work, however, is the role of contracts in obtaining faculty cooperation rather than the role of appropriability.

In this paper, we exploit a unique database that allows us to address directly the issue of whether private firms would adopt and commercialize university inventions in the absence of strong property rights to the technology. We examine the population of 805 attempts by private sector firms to commercialize inventions assigned to the Massachusetts Institute of Technology and licensed exclusively by the institution between 1980 and 1996. We use information obtained from the MIT technology licensing office on the dates of patent award and license execution, as well as the timing of subsequent commercialization of those inventions or termination of the licenses. We examine the relationship between the length of patent protection remaining on the inventions as well as other measures of appropriability and commercialization efforts. We argue that the length of patent protection remaining on an invention provides an incentive for private firms to commercialize university inventions. However, given the early stage of most university technologies, their commercialization takes time, initially increasing the probability of commercialization and decreasing the probability of termination because the probability that development will yield a commercially viable product increases over time. We also argue that other measures of appropriability, such as patent effectiveness and patent scope, increase the hazard of first sale and decrease the hazard of termination.

In Sections 2 and 3, we present a model of exclusive licensing in which a single firm that has licensed a university invention decides in each period whether to invest in further development, thereby increasing the probability of (technical) success, or to terminate the project. If the firm is successful at commercialization, it earns monopoly profit until the patent expires. If successful, the firm sells its new product immediately. Because of the opposing effects of length of remaining patent protection and effect of time on the probability of technical success, we find that patent age may have non-monotonic effects on both the hazard of termination and the hazard of first sale. The model predicts that for inventions with a sufficiently low initial probability of technical success, the hazard of termination has a u-shape and the hazard of first sale has an inverted u-shape, a pattern that we find in our data. The model also supports the view that wider patent scope and more effective patents decrease (increase) the hazard of termination (commercialization) regardless of patent age.

In sections 4 and 5, we present the data and empirical results for competing risks regression models to predict the hazard of first sale and license termination for 805 attempts to commercialize MIT-assigned patents licensed exclusively between 1980 and 1996. We find strong support for a u-shaped relationship with the age of the patent and the hazard of termination and somewhat weaker support for an inverted u-shaped relationship between the hazard of first sale and patent age. We also find that several other measures of appropriability, most notably the effectiveness of patents in a line of business and Lerner's index of patent scope, increase the hazard of first sale and decrease the hazard of termination. Our results are robust to controlling for the general technical field in which the invention is found, and the source of funding for the invention.

These results contribute, not only to the growing literature on innovation based on university research, but also to the broader literature on the relation between patents and innovation. As emphasized in a recent survey by Gallini (2002), the link between patent strength and innovation is, in general, ambiguous. Models which examine the relation between R&D spending and patent length in the presence of uncertainty find they are positively related (see Kamien and Schwartz, 1974 and Goel, 1996). However, Horowitz and Lai (1996) find an inverse u-shape relationship between patent length and the rate of innovation, and Lerner (2002) finds empirical support for such a relationship. In this work, the negative effect of patent length on innovation comes from taking into account the cumulative process of innovation and strategic effects from subsequent research.[4] Our results differ in that we explicitly incorporate the uncertainty associated with development of university inventions and we abstract from strategic issues.

Finally, we contribute to the empirical literature on the effectiveness of patents in appropriating returns from R&D. Much of this work focuses on the effectiveness of patents relative to other mechanisms and differences in appropriability across industries and countries (see, for example, Levin et al., 1987, Cohen et al., 1998, and Cohen et al., 2000, Lanjoux and Cockburn, 2000). While a few studies examine whether products or processes would not have been developed in the absence of patents (Taylor and Silberston, 1973, Mansfield, 1986, and Mansfield et al., 1981), their evidence is based on perceptions of R&D personnel responding to surveys. To our knowledge, ours is the only study to directly examine the relationship between patent characteristics and commercialization or termination of projects.

2 The Model

In this section, we consider the problem faced by a firm that has licensed a university invention which requires further development before it can be successfully commercialized. We assume that the firm has an exclusive license agreement with the university so that if development is successful, it will earn monopoly profits per period until the patent expires, which occurs at $L \geq 2$.[5] The age of the patent at the time of license is given by a, $a \in \{0, \ldots, L\}$, and licensing periods are indexed by t, where $t \in \{0, \ldots, L - a\}$, so that $a + t$ represents patent age in period t of the license.

To successfully commercialize the invention, the firm must invest c per period. This running development cost includes not only internal costs but also payments to the university, such as milestones, minimum royalties, and sponsored research. The returns to this investment are uncertain for both technical and market reasons. In a recent survey of businesses that license-in university inventions, Thursby and Thursby (2003) found that 46% of all inventions licensed fail and of these 47% failed

[4]Kamien and Schwartz (1974) find a negative relation between rivalry and the magnitude of innovation.

[5]As a matter of fact, $L = 17$.

for purely technical reasons. This is not surprising since roughly half of university inventions licensed are no more than a proof of concept at the time of license (Thursby et al., 2001). Moreover, defining market opportunities for early stage inventions is highly uncertain, so much so that many university inventions end up with applications that were not even anticipated at the time of license (Shane, 2000, and Thursby and Thursby, 2002).

We denote the probability the firm's development effort is successful by $p_t \in [0, 1)$ $\forall t$.[6] This function represents the technical probability of success. While investment may not increase the probability of success in any period, it is natural to assume that p_t is non-decreasing. The firm would not invest unless this were the case.[7] We further assume, as we believe is intuitive, that for any sequence of probabilities of success $\{p_n\}_{n=0}^{L}$, the probability of of success grows at a finite rate, that is, $\frac{p_{n+1}}{p_n}$ is finite for every n.[8]

Suppose the firm is successful in period t, then expected cumulative discounted profit is given by $\tilde{\Pi}_{a+t}(\delta)$ where δ is the discount factor ($\delta = (1 + r)^{-1}$ and $r > 0$ is the interest rate). Thus, from the firm's perspective, in any period before t, $\tilde{\Pi}_{a+t}(\delta)$ is a random variable with cumulative distribution function F_{a+t} on the interval $[0, \overline{\Pi}]$. We assume that the set of possible profit realizations is identical for all patent ages, but high realizations are more likely the younger the patent.[9] Formally, $F_n(B) \leq F_{n+1}(B), \forall n$. The distribution of profit outcomes when the patent is n years old first-order stochastically dominates the distribution of profit outcomes when the patent is $n + 1$ years old. This reflects two aspects of the patent aging: first, the number of periods the firm can earn monopoly profit declines, and second, the probability that a competing firm will commercialize a non-infringing substitute

[6]This is an important difference between our model and that of Horowitz and Lai (1996) who consider innovations that are a sure success.

[7]Thus we assume p_t is the true probability of success. An alternative, and more complicated model, would allow the firm'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.

[8]This rules out the probability of success jumping from an amount arbitrarily close zero to a non-zero amount. We assume that is p_t is close to zero, then so is p_{t+1}.

[9]It is not excluded that some of the outcomes in the interval will occur with zero-probability for some patent ages. We are thinking particularly about low (high) outcomes for low (high) patent ages.

increases (thereby reducing monopoly profit). Define $\mu_n \equiv E_n[\tilde{\Pi}_n]$, where E_n is the expectation operator. The subscript n indicates that the expected value is computed using F_n. We denote the sequence of expected profits, $\{\mu_n\}_{n=0}^{n=L}$, by $\mathcal{P}$. Given our assumption on the distribution function, μ_n is non-increasing in patent age.

If the firm is successful, it sells immediately. There are several reasons for this assumption. One is that it greatly simplifies the problem. In the Appendix we show how the firm's problem changes if it can delay selling. Second, and more importantly, the overwhelming majority of university licenses (and almost all of the MIT licenses) include minimum royalties or milestone payments designed to prevent licensees from delaying commercialization (Thursby et al., 2001). These payments, which we denote by $m \leq c$, reflect university attempts to ensure that the federal government does not "march-in" and exercise its right to find alternative licensees if it deems that the licensing firm "has not taken, or is not expected to take within a reasonable time, effective steps to achieve practical application of the subject invention."[10] In the context of our model, the assumption that $F_n(B) = 0$ for every $B \leq \delta\mu_{n+1} - m$ guarantees that the firm has no incentive to delay commercialization.

The firm's problem, then, is an optimal stopping problem similar to that analyzed by Roberts and Weitzman (1981).[11] Simply put, the firm's optimal decision rule is to continue in any period with a positive continuation value and stop as soon as the continuation value becomes zero. Using dynamic programming, the value of continuing at any t if the firm started to license when the patent was a years old can

[10]See Section 203 of the Bayh Dole Act. If the terms of the contract perfectly enforce "commercialization" one would expect march-in rights not to be exercised, and in fact they have not. In the public policy debates over Bayh Dole revision, Rai and Eisenberg (2002), argue that the march-in provisions should be strengthened.

[11]Our model is similar to their sequential decision process (SDP), although in their model, the SDP must go through a deterministic number of stages before completion. In our model, in every period, there is a positive probability that the current period is the period of completion. In this sense, our model bears many similarities to Grossman and Shapiro (1986), but their focus is on optimal development expenditure, rather than optimal stopping. They assume the value of investing is positive throughout so that termination is not an issue. Kamien and Schwartz (1971) examine similar problems under various assumptions about the probability of success. Optimal stopping problems have also been examined in the context of search (see Lippman and McCall (1976)) and diffusion of innovation (see Jensen, 1981; 2003).

be written as:

$$V_c(t, \Pi_{a+t}; a) = \max\{p_t \Pi_{a+t} + (1 - p_t)\delta E V_c(t+1, \tilde{\Pi}_{a+t+1}; a) - c, 0\}, \qquad (1)$$

where Π_{a+t} is the realized value of profit in period t. The expectation is taken over $\tilde{\Pi}_{a+t+1}$ and a is treated as a parameter. The terminal condition that ensures that the dynamic programming problem is well-defined is $\Pi_{L+1} \equiv 0$. When the patent expires, cumulative profits fall to zero with probability one. Given that success did not occur in $t-1$, (1) says that the value of continuing is equal to the maximum of 0, in which case the firm terminates the license, and profit if success occurs plus the value of continuing in the next period if development is unsuccessful, minus the development cost paid in the current period. We assume that $EV_c(0, \tilde{\Pi}_0; 0) > 0$ to ensure that the invention has a positive discounted expected value overall.

The optimal termination rule is simple: "*Continue to invest as long as $V_c > 0$. As soon as V_c drops to zero, terminate the license.*" Therefore the probability of termination conditional on neither termination, nor first sale, occurring before t is given by $p_f(t; a) = \Pr(V_c(t, \Pi_{a+t}; a) \leq 0) = F_{a+t}(B(t; a))$, where:

$$B(t; a) = \frac{c - (1 - p_t)\delta E V_c(t+1, \tilde{\Pi}_{a+t+1}; a)}{p_t}. \qquad (2)$$

$B(t; a)$ measures the net expected cost of continuing at period t, that is the development cost net of the discounted expected value of continuing in the next period, discounted by the probability of success in the current period.[12]

From $V_c(L+1-a; a) \equiv 0$, it follows that the firm terminates with probability one at $L+1$. Using this fact, the optimal stopping rule and first sale decision generate a well-defined probability distribution over termination dates in $\{0, \ldots, L+1-a\}$:

$$P_f(t; a) = p_f(t; a) \prod_{k=0}^{t-1} (1 - p_k)(1 - p_f(k; a)). \qquad (3)$$

Similarly, the optimal first sale decision generates a well-defined probability distribution over dates of first sale in $\{0, \ldots, L+1-a\}$:[13]

$$P_s(t; a) = p_s(t; a) \prod_{k=0}^{t-1} (1 - p_k)(1 - p_f(k; a)). \qquad (4)$$

[12] We suppress $\tilde{\Pi}_{a+t1}$ as an argument from $B(t; a)$ and the hazard functions defined below for notational convenience.

[13] $P_i(t; a) \leq 1$ for very t and $\sum_{t=0}^{L-a+1} P_i(t; a) = 1$, $i = f, s$.

The joint survival function in period t is the probability that the firm has neither terminated, nor commercialized in any period $k \in \{0, \ldots, t-1\}$. In the context of our model, it is given by:

$$s(t;a) = \prod_{k=0}^{t-1}(1-p_k)(1-p_f(k;a)) = \prod_{k=0}^{t-1}(1-p_k)(1-F_{a+t}(B(k;a))).$$

The hazard of termination in period t is the probability that the firm terminates in period t given that it neither terminated, nor commercialized before t and is given by:

$$h_f(t;a) \equiv \frac{P_f(t;a)}{s(t;a)} = p_f(t;a) = F_{a+t}(B(t;a)). \tag{5}$$

Similarly, the hazard of first sale t is given by:

$$h_s(t;a) \equiv \frac{P_s(t;a)}{s(t;a)} = p_s(t;a) = (1-p_f(t;a))p_t. \tag{6}$$

(6) represents the probability that the firm commercializes in period t conditional on the firm not having commercialized or terminated before t. It is straightforward to see that both hazard rates may decrease or increase as a patent ages. *Ceteris paribus*, an increase in a increases both the hazard of termination and the hazard of first sale because it increases the net expected cost of continuing given by (2). The question of interest, however, is how the hazard rates change over time given a.

3 Comparative statics

Comparative statics allow us to examine the effect of patent age, expected profit, and the probability of technical success on the firm's decisions. Not surprisingly, parameters that increase expected cumulative profits (such as patent scope and strength) decrease the hazard of termination regardless of patent age. Conversely, parameters that decrease expected profits (such as financial constraints) increase the hazard of termination regardless of patent age. The relation between patent age and termination is, as expected, more complex. The fact that an older patent provides exclusive legal rights for fewer periods provides an incentive for the firm to terminate sooner than if it held a more recent patent. However, the firm is more likely to be successful at development the longer it has invested, so that the effect of patent age $(a+t)$ on the hazard of termination may be non-monotonic. Finally, we show that the hazards of termination and first sale can be inversely related.

3.1 Termination decision

Consider, first, the effect of a more favorable distribution of profit outcomes on the hazard of termination. Proposition 1 below says that for two distributions of profit outcomes associated with an invention, the hazard of termination is lower in every period for the distribution with better outcomes than for the other distribution.

Proposition 1 *Given* a *and* δ*, if* $\{F'_n\}_{n=0}^{L}$ *and* $\{F_n\}_{n=0}^{L}$ *are such that for every* n*,* $F'_n(B) \leq F_n(B), \forall X$*, the hazard of termination is lower if the sequence of profit distributions is given by* $\{F'_n\}_{n=0}^{L}$ *than if it is given by* $\{F_n\}_{n=0}^{L}$*.*

Thus anything that improves the distribution of profits, such as wider patent scope or greater strength, will provide higher continuation values on average in every period of development and, therefore, a later termination date with lower probability of occurrence.

Ceteris paribus, factors that increase the firm's ability to appropriate returns from investment in the invention will have a positive effect on continuation independent of patent age. It is important to note, however, that patent characteristics associated with expected profits may have ambiguous effects on continuation. For example, inventions with fewer citations to prior art are more novel and may command higher monopoly profit, but their development is more uncertain. Assuming that less prior art increases the sequence of expected profit, $\mathcal{P}$, and decreases the probability of success in the first licensing period (p_0), the effect on the hazard of termination is ambiguous.

The same observation can be made regarding comparative statics on invention characteristics, such as whether the invention radically improves upon existing products or processes. Radical inventions are typically more difficult to develop, but yield higher monopoly profit if successful. In the model, more difficult development can be represented by a higher c, holding the sequence $\{p_n\}_{n=0}^{n=L}$ constant, which would increase the hazard of termination. On the other hand, higher profitability may counterbalance or overturn the effect of higher development costs. Therefore, it is not clear whether higher radicality should increase or decrease the hazard of termination.

In Proposition 2, we consider the effect of the discount factor δ. The traditional interpretation for δ is that it measures the interest forgone by investing in the project for one more period. Alternatively, we can view δ as a measure of the interest rate paid by the firm on loans associated with the investment, with a lower δ representing a higher interest rate. Proposition 2 follows from taking the view that δ represents the importance of financial constraints faced by the firm:

Proposition 2 *Given a, firms that face looser financial constraints have lower hazards of termination.*

Proof. See Appendix.

Finally, we consider the effect of patent age on the firm's decision to terminate the license in a particular period. Holding t constant, simple comparative statics show that $\frac{\partial B(t;a)}{\partial a} \geq 0$. Therefore, in any given period, a license executed for an older patent will have a higher probability of termination and thus, a higher hazard of termination. However, time may have a positive effect on the continuation value through increased development effort, or a higher probability of success.

Proposition 3 *Given the parameters of the model, if the distribution of profit outcomes changes slowly with patent age and the probability of technical success is low and increases slowly initially, then the hazard of termination decreases with patent age if the patent is young. Otherwise, the hazard of termination increases with patent age.*

Proof. See Appendix.

Patent age has an ambiguous effect on the hazard of termination because of the two opposing dimensions of time. As time passes, the chances that the firm's investment will yield a highly profitable product decrease (F_{a+t}) as the periods remaining on the patent decrease (and therefore the length of time it can earn monopoly profit), but the probability that the invention will lead to a product increases (p_t). In order for the hazard of termination to decrease over time, it must be the case that the positive effect of the increasing probability of technical success over time outweighs the negative effect of the distribution of profit outcomes over time. This suggests that if the hazard of termination ever decreases with patent age, then it must be for low patent ages, when the firm still expects relatively high cumulative profits, and the invention is at an early stage of development.

3.2 Commercialization decision

Recall from Section 2 that termination and the date of first sale are closely related. More precisely, the hazard of first sale increases if the hazard of termination decreases. Therefore, an increase in expected profit throughout the life of the patent decreases the hazard of termination, and thus increases the hazard of first sale, for every patent age.

Proposition 4 *Given a and δ, if $\{F'_n\}_{n=0}^{L}$ and $\{F_n\}_{n=0}^{L}$ are such that for every n, $F'_n(B) \leq F_n(B), \forall X$, the hazard of first sale is higher if the sequence of profit distributions is given by $\{F'_n\}_{n=0}^{L}$ than if it is given by $\{F_n\}_{n=0}^{L}$.*

To the extent that wider patent scope or strength increase expected profits, it follows that they increase the hazard of first sale for every patent age.

The hazard of first sale therefore increases whenever the probability of first sale increases. It decreases, however, only if the probability of first sale decreases enough. In a given development period, older patents represented by a higher a have a lower hazard of first sale simply because the probability that the license has not been terminated before reaching this development period is lower. The effect of development for a given age at the time of the license is ambiguous. We have the following proposition:

Proposition 5 *Given the parameters of the model, if the hazard of termination decreases with patent age, then the hazard of first sale increases with patent age. If the hazard of termination increases with patent age, the hazard of first sale could still increase if the probability of technical success increases sufficiently fast.*

Proof. See Appendix.

Note that even if the hazard of termination increases with patent age, this is not sufficient for the hazard of first sale to decrease for all patent ages.

In summary, the model implies a strong relationship between the hazards of termination and first sale because of the timing of decisions. We find that better appropriability in the sense of wider patent scope or more effective patents increases both the hazard of termination and the hazard of first sale. On the other hand, better appropriabiltity as measured by the age of the patent can have non-monotonic effects on both hazard functions. This ambiguity comes from the opposing effects of continued investment on the technical probability of success (a positive effect) and the decrease in the number of periods left on the patent (a negative effect). The shape of the hazard functions over time is therefore an empirical issue. Recall, however, that our assumptions on the probability of technical success are based on empirical evidence on the embryonic nature and high failure rate of university inventions. If we were to assume that the probability of success is initially close to zero, but increasing over time at a decreasing rate (i.e., diminishing returns to development), then one would expect the hazard of termination to decrease initially but eventually flatten out and perhaps increase.

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 subsequently licensed exclusively 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 exclusively to at least one private firm.

Our data 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.

Since our theoretical model provides hypotheses regarding the behavior of firms with exclusive licenses, we condition the empirical analysis on the TLO having licensed the invention exclusively. There are 805 exclusive attempts corresponding to 2845 periods in which licenses were at hazard.[14] While it is plausible that licenses are terminated after commercialization, the MIT licensing office 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.[15]

Table 1 reports the unconditional survival rates and the extent of right censoring for the sample of patents licensed exclusively. First and foremost, firms are far more likely to terminate licenses of patents than successfully commercialize them (288 terminations vs. 168 successes). The table also suggests that uncertainty associated with an innovation is generally resolved in the first 5 years of license. Note that from the 6th year on, the conditional probabilities are based upon small samples. 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. Figure 1 shows the reduced-form event hazards of termination and commercialization. The sparseness of this right tail implies that there is little information on which to estimate the baseline hazard. Therefore, we recoded all observations that survived more than five periods as right censored after five periods. Thus, in addition to the observations that are right-censored after 1996, we censored an additional 74 observations.

This does *not* mean that uncertainty is resolved within five years of issuance of a patent. As is evident in table 2, it is not uncommon for patents of medium age to be licensed, although this is very uncommon for old patents. It is not uncommon for licenses to survive well into patent life before first sale or termination (table 3).

[14]Although we leave their analysis for future work, there are only 163 non-exclusive licenses in the full sample. Very few patents are licensed exclusively in all fields of use and almost nothing is licensed non-exclusively. It is straightforward to define a field of use and the scope of a field is very flexible, so both sides are generally able to agree on a field of use in negotiation.

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

85% of licenses are resolved before patents reach age 11.

The variation in patent age at the time of license allows us to distinguish between 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 in the baseline hazard estimates, while the latter are measured in the coefficients on age. This distinction is important because the age of the license captures the effects of firm learning. If the effects of patent age on first sale and termination are as predicted, this means that the effects exist even after the effects of firm learning about the commercialization of the technology have been controlled for.

Table 4 shows descriptive statistics for our analysis. We include several variables in our regressions. We measure AGE OF PATENT as the number of years since the patent was issued.

We employ several complementary measures to control for the quality of the patent. First, we use 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. As implied by Propositions 1 and 4 respectively, PATENT SCOPE should be negatively related to the hazard of termination and positively related to the hazard of first sale.

Second, PRIOR ART CITED measures the number of prior patents cited by the focal patent. Out theory is ambiguous as to the expected signs of the coefficients on this variable. A decrease in prior art is associated with more novel and hence more risky knowledge, which should increase the hazard of termination. However, a decrease in prior art expands the scope of the property rights covered by the focal patent, which should decrease the hazard of termination, *ceteris paribus*.

Third, we employ 4 measures from the Yale survey on innovation (Levin et al., 1985; Levin et al., 1987). These measures are derived from managers opinions as to the effectiveness of different mechanisms used to appropriate the returns to innovation for process or product R&D in a line of business. The managers were asked to rate mechanisms on seven point Likert scales. The mechanisms are: patents prevent duplication; patents secure royalty income, secrecy, lead time, moving down the learning curve, and complementary sales and service efforts. We measure PATENT

STRENGTH as the average score for both patent measures for product and process innovations. As with PATENT SCOPE, PATENT STRENGTH should be negatively related to the hazard of termination and positively related to the hazard of termination. Using the Yale survey measures, we also examine the effects of SECRECY, LEAD TIME and moving down the LEARNING curve as the average score on each dimension for product and process innovations. We match the Yale survey line-of-business scores to patents by using the Yale survey concordance with SIC codes and the US Patent and Trademark Office's SIC-to-patent concordance.

We include several additional control variables in the hazard predictions. These variables are all designed to control for the commercial aspects of development. First, we include a dummy variable that takes the value one if the licensee is a START-UP, which we define as a company not in existence prior to the licensing of the patent. STARTUP should influence the termination, which could occur if the company, rather than the technology failed. There is much additional risk associated with commercializing through a startup that is associated with setting up the new firm's infrastructure, and startups may also be liquidity-constrained relative to established firms. These factors suggest that new firms should discount the future heavily. Proposition 2 implies that these factors should increase the likelihood of termination. Recall from section 2 that this implies that the hazard of first sale should be decreasing in these factors.

Second, we control for the RADICALNESS of the invention. Following Shane (2001) and Rosenkopf and Nerkar (2001), we measure the RADICALNESS as a count of three-digit classes in which previous patents cited on the focal patent are found, but that the patent itself is not in. Following our discussion of proposition 1, we have no prior expectation of the relationship between RADICALNESS and the hazard of termination and commercialization. Radical technologies are more difficult to develop, but generate more profit if they are successfully developed.

Third, we include a dummy variable that takes the value one if the research that led to the invention was industry funded. Industry funded research is more likely to be directed, in the sense that firms are likely to expect tangible beneficial results from the research or the relationship with the investigator. Indeed, Goldfarb (2002) and Mansfield (1995) both find evidence consistent with the idea that the congruence of research goals is an important consideration in the research grant matching process.

We expect that INDUSTRY FUNDING should decrease the hazard of termination, and increase the hazard of first sale. Firms should be less likely to terminate efforts to commercialize inventions funded by themselves or competitor firms, as the results are likely to be more closely related to their strategic goals. Likewise, we should expect that industry funded research is more likely to result in a commercial product, as results stemming from such research would be more commercially relevant.

Fourth, we include a measure of a patent's GENERALITY following Hall, Jaffe and Tratjenberg (2001).

$$GENERALITY_i = 1 - \sum_{i}^{n_i} s_{ij}^2 \tag{7}$$

where s_{ij} is the percentage of citations received by patent i that belong to patent class j out of n_i patent classes. A high score suggests that a patent has been a component of inventions in many different patent classes, and hence more general. If more general technologies take longer to apply to particular applications, then we should expect the termination and commercialization decisions to be made more slowly for general inventions than for less general ones.

Finally we include TECHNOLOGY CLASS dummies. Following the Hall, Jaffe, and Trajtenberg classification of patents, we break the patents into five categories: drugs, electronics (including computers and communications), chemicals, mechanical, and other. We might expect drugs to take longer to reach first sale due to FDA regulations than, say, mechanical devices.[16]

5 Empirical Results

Our theory models the empirical reality in which attempts to commercialize patented inventions are either successful, in which case we observe a first sale, are terminated by either one of the parties of the license or by default if the patent expires, or are retained with neither event occurring. The appropriate empirical model for this is a competing risks model which must adjust for right censoring and the discrete nature

[16]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.

of the data. For detailed descriptions of competing risks models see Kalbfleisch and Prentice (1980) and Lancaster (1990). 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 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, $S(k_f, k_d|x)$, if there is sufficient variation in the vector of regressors x (McCall 1993, 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:

$$\Pr(T_d = k|X, T > k-1) = 1 - \exp(-\theta_d \exp(\alpha_{dk} + \beta_d' x)), \tag{8}$$

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

$$\Pr(T_f = k|X, T > k-1) = 1 - \exp(-\theta_f \exp(\alpha_{fk} + \beta_f' x)), \tag{9}$$

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:

$$S(k_s, k_d|x) = \exp\left(-\theta_f \sum_{r=1}^{k_f} \exp(\alpha_{fk} + \beta_f' x) - \theta_d \sum_{r=1}^{k_d} \exp(\alpha_{dk} + \beta_d' x)\right). \tag{10}$$

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

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

where $\lambda_w(t)$ 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 $2nd$ order polynomial. A 2nd-order polynomial is sufficiently flexible to approximate a baseline hazard function of only five periods. Thus

$$\alpha_{wk} = \alpha_{0k} + \alpha_{1k}k + \alpha_{2k}k^2. \quad (11)$$

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

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

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 identified in the labor literature with competing risks models 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, the risks correlate by allowing a two mass-point distribution of location parameter pairs θ_{dj}, θ_{fj} where j=1,2. Each pair occurs with probability q_j. The four location parameters and one free probability are estimated by the data. Thus,

$$\wp_w(k) = \sum_{j=1}^{2} q_j P_w(k|\Theta_j) \quad (12)$$

The log-likelihood is:

$$\log\ L = \sum_{n=1}^{N}\sum_{k=1}^{K_n} d_{fk}^n \log \wp_{fk}^n + d_{dk}^n \log \wp_{dk}^n + (1-d_{fk}^n)(1-d_{dk}^n) \log \wp_{ck}^n. \quad (13)$$

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.

We report the robustness of our results with respect to the different methodologies in table 5. The proportional hazards models reported in regressions a1 and a2 foreshadow the results of the more sophisticated competing risks models. In a1, an event is termination of a license, while in a2 an event is the first sale of a license. That is, the first model does not distinguish between right censoring and first sale, whereas the second model does not distinguish between right censoring and termination. Nevertheless, we find a u-shaped relationship between the patent age and the hazard of termination and more weakly find an inverse u-shaped relationship between patent age and first sale.[17]

In regression 5b we report the results of competing risks models with independent risks.[18] The coefficients on AGE and AGE^2 clearly depict a u-shape relationship between patent age and the hazard of termination that reaches its low point when patents are eight years from issuance. This relationship is robust to controlling for whether or not the firm was a START-UP, whether the research leading to the patent was funded by industry, the PATENT SCOPE, PRIOR ART CITED, the RADICALNESS and GENERALITY of the patent, potential macroeconomic effects (period dummies), the TECHNOLOGY CLASS dummies and the appropriability mechanisms that are effective in the line of business.

However, our results concerning the influence of PATENT AGE on the hazard of first sale do not show a curvilinear relationship between PATENT AGE and the hazard of first sale. In an unreported regression, we find that if we drop the quadratic term, the coefficient on patent age is positive and significant when risks are restricted to be independent.

In regression 5c we allow for correlated risks. We strongly reject the hypothesis that there is no unobserved heterogeneity (LR statistic = 63.24).[19] We continue to

[17]Note that whereas in the competing risks regressions we report estimated coefficients, in these two regressions we report the proportional change in hazard with a unit change in the independent variable.

[18]To map this regression onto the likelihood function, note that only one mass-point is allowed, i.e, one $\{\theta_d, \theta_f\}$ pair. That is, we restrict α_{12}, α_{22}, θ_{21}, θ_{22} and q_2 to 0.

[19]It is interesting to note that the unobserved components seem to be positively correlated. We

robustly find that the hazard of termination has a u-shape in patent age, although our standard errors are larger than in the restricted regressions. Similarly to regression 5b, we find evidence that the hazard of first sale has an inverted u-shape in patent age or is relatively flat, although here the signal is slightly stronger, as the z-statistic on the quadratic term moves from -1 to -1.4.

In table 6 we explore the sensitivity of the results to the inclusion of various controls. Regardless of the controls we add, we find a u-shaped relationship between PATENT AGE and the hazard of termination. We see little difference of the effect of PATENT AGE on the hazard of first sale when we add additional controls in regressions 6a and 6b as compared to regression 5c.

One possible explanation for the null results for commercialization and the significant results for termination is that they are artifacts of different commercialization horizons for different technologies. Therefore in regression 6c, we interact the TECHNOLOGY CLASS dummies with PATENT AGE. We find no statistically significant differences by technology in the effects of age on either commercialization or termination. Moreover the u-shaped relationship of PATENT AGE and termination is robust to the inclusion of these interaction terms. For commercialization, the inclusion of these interaction terms allows us to measure the effect of the inverse u-shaped relationship between PATENT AGE and commercialization with more precision. In regression 7c the linear term is significant and positive while the quadratic term is marginally significant and negative at the 90% level.

However, in the commercialization regression, we fail to reject the null hypothesis that each coefficient is zero when we add time-period controls in regression 6d. In particular, when we take into account whether the decision occurred between 1980-1984, 1985-1989 and 1990-1996, the z-statistics drop to about 1.4. Indeed, a likelihood ratio test fails to reject the hypothesis that the PATENT AGE and PATENT AGE^2 coefficients are jointly zero in this regression. The results for termination remain robust to the inclusion of period effects.

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} and θ_{12} as picking up high-quality patents, and θ_{21} and θ_{22} as picking up low quality patents. In this case the model is predicting much lower hazards of events with high quality patents than low quality patents, and that 46% of the patents are high quality.

Table 7 provides a robustness check for the quadratic form of the relationship between age and termination, and age and first sale. When we remove the quadratic term from the first sale equation we do not find a monotonically increasing function, rather we find a zero coefficient on the linear patent age term (regression 7b). Nor do we find any evidence of a cubic relationship (regression 7a). Our data suggest that if there is a relationship between PATENT AGE and the hazard of first sale, a quadratic form fits the data best. However, the signal is weak and our data are too noisy to measure it convincingly.

In contrast, the hypothesis that the PATENT AGE and PATENT AGE^2 coefficients are jointly zero in the termination equation is rejected at the 95% level. In regression 7d we see that the relationship is clearly not linear. Interestingly, the cubic form seems to fit reasonably well in regression 7c. The shape of this cubic function predicts a modestly increasing function until a patent is three years of age followed by an inverted-u that reaches a minimum when at 11 years and increases through the age of 17. However, the null hypothesis that the cubic form does not explain the data any better data any better than the quadratic form cannot be rejected at the 90% level.

In addition, we measured the relationship using 14 age dummies for PATENT AGE and PATENT AGE^2. Applying all time constant controls, the data predict a u-shape for termination, and we generally measure zero coefficients for the hazard of first sale.[20]

In short, we are quite confident that there is a u-shaped relationship between a patent's age and the hazard of termination, whereas we find a relatively flat relationship between a patent's age and the hazard of first sale. We offer two explanations for this weak result for the first sale hazard. The first is that there is simply less information about commercialization in the data than termination. In table 1 we see that 18% (146 of 805) of the patents are commercialized by the fifth period. Second, the decision to sell is subject to more factors beyond the control of the decision makers than the decision to terminate. For example, an intent to commercialize can be confounded by such exogenous factors as the state of the underlying technology or market demand. As a result, it is likely more difficult to measure the factors

[20] This pattern becomes clear after smoothing with three-year moving averages. These regressions are available from the authors upon request.

that influence technology commercialization precisely than the factors that influence license termination.

We base our analysis of the magnitude of the effects on regression 5c. We report the mean predicted hazards of termination and first sale for all licenses at various simulated patent ages in period 2. The results for termination appear in figure 2. A 95% confidence interval is also depicted. As we can see, increasing the age by one year for a patent of mean age (5) increases the hazard probability of termination by 0.006 (since the mean predicted hazard of 5 year old patent is 0.06; this implies a 10% decrease in the predicted hazard). The effect begins to reverse itself as a patent reaches age 9. In Figure 3 we present the similar graph for the hazard of first sale. Here the hazard of first sale increases by 7% when patent age increases from age 5 to 6. The figures also depict 95% confidence intervals for these estimates. As expected, the intervals are at their narrowest points at the mean age of 5. Reflecting our general results, they are much narrower in figure 2 (termination).

Recall that propositions 1 and 4 give unambiguous implications for PATENT STRENGTH and PATENT SCOPE on the hazards of termination and first sale, respectively. Across all our regressions, we find a robust positive effect for the PATENT STRENGTH in a line of business on the likelihood of first sale and a robust negative effect on the likelihood of termination. Because these measures are derived from a Likert scale, we look at effect of a change in one standard deviation from the mean. If managers in a line of business rated the effectiveness of patents one standard deviation higher than the mean for all other lines of business, the hazard of termination decreased by 0.003 which is a 5% hazard change (this difference is significant at the 99% level). An increase in one standard deviation from the mean increases the hazard of first sale by 0.004 which is a 7% hazard change (this difference is significant at the 99% level). We also find a robust effect of PATENT SCOPE on first sale across all regressions, although we do not find such an effect on termination. With regards to patent scope, if each sample patent had spanned one additional category, then the mean increase of hazard of first sale would be 0.029 or 59% (difference significant at the 95% level). As anticipated by our discussion of comparative statics in Section 3, we find non-robust results for the effects of PRIOR ART CITED. Although not always measured precisely, patents that cite more prior art are more likely to be terminated.

Though speculative, we also find other interesting empirical results. As we would expect, licenses of innovations stemming from INDUSTRY-FUNDED research are less likely to be terminated. On average, the predicted decrease in hazard of termination of a license of a patent stemming from research funded by industry is 0.04 (difference significant at the 95% level). This reflects a 57% decrease in the predicted hazard. There is no consistently measurable effect on the hazard of first sale. This suggests that INDUSTRY-FUNDED inventions are valuable, but take longer to commercialize. We note that this result is consistent with firm's shelving industry funded inventions.

Our results concerning the licensing to a STARTUP and both commercialization and termination are intriguing. In table 6 we find that the hazard of termination *and* first sale decrease if the technology is licensed to a STARTUP. This result is sensitive to allowing for unobserved heterogeneity, whereas the first sale result is sensitive to the inclusion of time dummies. This result does not match the prediction of proposition 2 and is left for further study.

In some regressions we find that technologies that have broader applications are also more difficult to commercialize. However, the significance of this result is highly dependent on the specification. One might speculate that the nature of general technologies is such that they are farther from a commercial application. That is, less specialized technologies are less likely to be immediately useful.

Finally, technologies that are more radical are more likely to be commercialized. Again, this result is sensitive to specification, although it does not disappear with the inclusion of various controls (see regression 6d). Each additional three-digit class that previous patents cited on the focal patent increases the hazard of first sale by 0.004, which is 8%. This difference is significant at the 95% level. This result suggests that the increase profit potential of radical technologies overwhelms the increased risk associated with such technologies.

6 Conclusions

In this paper, we argue that keys to understanding much of the Bayh-Dole policy debate are none other than the problems of appropriability and uncertainty identified by Arrow (1962) nearly a half a century ago. To do so, we examine a model of exclusive licensing in which a single firm has licensed a university invention that requires further development in order to be successful commercially. Success is uncertain for both technical and market reasons. In each period, the firm decides whether to invest in further development, thereby increasing the probability of (technical) success, or to terminate the project. If the firm is successful at commercialization, it earns monopoly profit until the patent expires. We then characterize the hazard of termination and first sale as a function of the patent age, expected profit, and the probability of technical success. Parameters such as patent scope and strength which increase expected cumulative profits decrease the hazard of termination regardless of patent age. The relation between patent age and termination is, however, more complex. The fact that an older patent provides exclusive legal rights for fewer periods provides an incentive for the firm to terminate sooner than if it held a more recent patent. However, the probability the invention will succeed technically is higher the longer the firm has invested, so that the effect of patent age $(a+t)$ on the hazard of termination may be non-monotonic.

Our empirical results provide strong support for the view that the ability to appropriate returns is important for inventions whose success is highly uncertain. We find that increased appropriability, as measured by Lerner's index of patent scope and effectiveness of patents in a line of business, decrease the hazard of termination and increase the hazard of first sale. We find a u-shaped hazard of termination which is consistent with the opposing effects of time on the probability of success and appropriability as measured by the length of time left on the patent in the model. Our results on the hazard of first sale are less robust. The theory suggests that, if the firm sells as soon as the invention is successful technically, the hazards of termination and first sale will be inversely related. However, our empirical results show a flatter hazard of first sale.

Several caveats may explain the latter result. First, note that our characterization of the hazard of first sale and termination is based on the assumption that the firm introduces the invention to the market as soon as it is successful. If delaying first sale is profitable, the hazard for first sale and termination need not be inversely related, and in fact, we cannot characterize the relation. A variety of factors related to strategic or other aspects of the market could clearly make delaying first sale optimal. Second, 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 march-in rights contained in the Bayh-Dole Act, 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 a profitable strategy for firms to maintain the license, preventing competitors from having access (as would be the case if the invention were returned to MIT). While we cannot eliminate this possibility nor identify when it might be happening, we suspect that our first caveat is more likely given the importance that technology transfer offices attach to due diligence in order to prevent shelving.[21]

Finally, note also 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.[22] Hence, a result of a terminated patent (license) is not necessarily indicative of lack of technology transfer, or of a technology failure in general, except in the sense that the university, and perhaps inventor if a complementary consulting arrangement does not exist, will not receive rents (Henrekson and Goldfarb, 2002).[23]

These caveats aside, our results contribute to the growing literature on innovation based on university research. While much research has focused on spillovers through publications, consulting, and conference participation (see, for example, Adams, 1990; Agrawal and Henderson, 2002; Cohen et al., 1998; Jaffe, 1989; Mans-

[21]Recall that Thursby et al (2001) found this in their survey of 62 universities. In the particular case of MIT, several companies lost their licenses when they did not make annual payments or failed to meet a milestone. This is, of course, much more common with start-ups and small firms. In many cases, writing a business plan was a milestone and when the plan was not delivered, the firm would lose its license.

[22]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.

[23]Under the invent-around scenario the university may still receive rents if the license involved the transfer of equity to MIT. In this case returns are tied to profitability of the firm, rather than profitability of the specific licensed patent. Since equity is permanent, MIT could earn returns even if a particular invention were terminated. This may explain differential use of equity in licensing agreements across types of technology.

field, 1995; and Zucker et al., 1998), relatively little empirical research has explored the licensing mechanism, and in particular the question of whether private firms would adopt and commercialize university inventions in the absence of strong property rights to technology. Our results support the key principle underlying the Bayh-Dole Act. The ability to appropriate the returns to investment in innovation enhances the commercialization of technology licensed by universities to private firms.

Our results also contribute to the broader literature on the relationship between patents and innovation. Gallini's (2002) review indicates that the link between patent length and innovation is ambiguous, in general, but may have an inverted u-shape because of the incentives associated with entry. We contribute to this literature by showing that, even without sequential innovation, the combined effects of uncertainty and appropriability lead to an inverted u-shaped relationship between patent age and the hazard of first sale and a u-shaped relationship between patent age and the hazard of license termination.

Lastly, we contribute to the empirical literature on the effectiveness of patents in appropriating returns from R&D. In contrast to prior studies based on surveys of the perceptions of R&D personnel, we provide direct empirical evidence of the relationship between patent characteristics and commercialization of products or termination of projects.

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7 Appendix

7.1 Delaying first sale

To simplify notation, we let $m = 0$, in which case the license includes no financial incentives to prevent the firm from delaying first sale. If the firm is able to maintain its license without selling even after development has been successful, it compares the value of profits it can achieve by commercializing this period to the value it could achieve by delaying optimally. Since $\mu_{a+t+s} < \mu_{a+t+1}$, given the information available to the firm at period t, it does not anticipate delaying for more than one period. Therefore the value function writes:

$$V_c(t, \Pi_{a+t}; a) = \max\{p_t \max\{\Pi_{a+t}, \delta\mu_{a+t+1}\} + (1 - p_t)\delta E V_c(t + 1, \tilde{\Pi}_{a+t+1}; a) - c, 0\}. \tag{14}$$

Since $\mu_{a+t} > \delta\mu_{a+t+1}$, it is clear that $EV_c(t, \Pi_{a+t}; a)$ is unchanged as compared to the case where delaying is not possible.

Suppose $\Pi_{a+t} < \delta\mu_{a+t+1}$ so that the firm chooses to delay first sale, then (14) becomes:

$$V_c(t, \Pi_{a+t}; a) = \max\{p_t\delta\mu_{a+t+1} + (1 - p_t)\delta E V_c(t + 1, \tilde{\Pi}_{a+t+1}; a) - c, 0\}. \tag{15}$$

The ability to delay bounds the value of V_c below, and possibly, away from 0. If $V_c(t, \Pi_{a+t}; a) > 0$, then the firm continues. If not, the firm stops. Therefore, in any period t for which $V_c(t, \Pi_{a+t}; a)$ given by (15) is greater than zero, the firm will continue with probability 1. The reservation value that governs the optimal termination decision is below the reservation value that governs the optimal first sale decision. If $V_c(t, \Pi_{a+t}; a)$ given by (15) is less than zero, then the firm will never delay, and the value function is effectively given by (1). The reservation value that governs the optimal termination decision is higher than the reservation value that governs the optimal first sale decision.

If the firm succeeded at t, its dynamic programming problem reduces to choosing the optimal date of first sale according to the following value function:

$$V_s(t, \Pi_{a+t}; a) = \max\{\Pi_{a+t}, \delta\mu_{a+t+1}\}.$$

The terminal condition is given by $V_s(L + 1) \equiv 0$.

Suppose that there exists a set D of consecutive periods in which (15) is greater than zero. Then the probability that the firm will sell in some period $t \in D$ is:

$$q_s(t;a) = [1 - F_{a+t}(\delta\mu_{a+t+1})][p_t \prod_{s=0}^{t-1}(1-p_f(s;a))(1-p_s) + \sum_{s=1}^{t-\min\{D\}} p_{t-s} \prod_{i=0}^{t-s-1}(1-p_f(i;a))(1-p_i)\prod_{i=1}^{s} F_{a+t-i}(\delta\mu_{a+t-i+1})]. \quad (16)$$

The first bracketed term is the probability that the firm will not delay in period t. The first part of the second bracketed term the probability that the firm is successful in period t, and the second part is the probability that the firm was successful in a period of D different from t, but chose to delay. Thus, although we can compute the probability of first sale in a given period t, given that the firm could have optimally delayed sales in previous consecutive periods, characterizing the hazard of first sale is intractible.

7.2 Proof of Proposition 2

Given a, let $\hat{t}(a) < L - a$ be that period of time for which:

$$p_{\hat{t}(a)}\mu_{a+\hat{t}(a)} - c \geq 0 \text{ and } p_t\mu_{a+t} - c < 0, \forall t > \hat{t}(a).$$

Then, $EV_c(\hat{t}(a)+1;a) = 0$. Using (1) and working backward from $L-a$, we obtain for $t < \hat{t}(a)$, and some realization of $\tilde{\Pi}_{a+t}$:

$$EV_c(t;a) = \max\{p_t\mu_{a+t} + \sum_{n=0}^{\hat{t}(a)-t-1} \delta^n \prod_{i=1}^{n}(1-p_{t+i})(p_{t+n+1}\mu_{a+t+n+1} - c), 0\}. \quad (17)$$

Differentiating $B(t;a)$ given by (2) with respect to δ yields $\frac{\partial B(t;a)}{\partial \delta} \leq 0$. This implies that for a given patent age $a+t$, the probability of termination decreases with δ, which in turn implies that if $\delta' > \delta$, the hazard of termination at $a+t$ is lower at δ' than at δ.

7.3 Proof of Proposition 3

We wish to find conditions under which the hazard of termination decreases with patent age. A necessary condition for the hazard of termination to decrease with patent age is for a given a, $B(t+1;a) < B(t;a)$. A sufficient condition is that the distribution function does not change rapidly between $a+t$ and $a+t+1$. Since $\tilde{\Pi} \in [0, \overline{\Pi}]$, if $c \leq \delta(1-p)EV_c$, then $X \leq 0$, and thus $p_f = 0$. Therefore, in the analysis below, we assume that $\delta(1-p_t)EV_c(t+1;a) - c < 0$. Using (2), $B(t+1;a) < B(t;a)$ if and only if:

$$\frac{p_{t+1}}{p_t} \geq \frac{c - \delta(1-p_{t+1})EV_c(t+2;a)}{c - \delta(1-p_t)EV_c(t+1;a)}. \tag{18}$$

The left-hand side is strictly greater than 1, so the condition will definitely be satisfied if the right-hand side is less than or equal to 1. This is the case if and only if:

$$\frac{EV_c(t+2;a) - EV_c(t+1;a)}{p_t} \geq \frac{p_{t+1}}{p_t}EV_c(t+2;a) - EV_c(t+1;a) \tag{19}$$

Given $EV_c(t+2;a) - EV_c(t+1;a) > 0$, then if (19) is satisfied, it must be the case that $\frac{p_{t+1}}{p_t}$ and p_t are small enough. p_t cannot be too small (for example, p_t must be bounded away from 0). We need to find conditions under which $EV_c(t+2;a) - EV_c(t+1;a) > 0$. Suppose $EV_c(t+2;a) > 0$ and $EV_c(t+1;a) \geq 0$. Using (1), we have:

$$EV_c(t+2;a) - EV_c(t+1;a) = [1 - \delta(1-p_{t+1})]EV_c(t+2;a) - (p_{t+1}\mu_{a+t+1} - c), \tag{20}$$

If $p_{t+1}\mu_{a+t1} \leq c$, then (18) is definitely satisfied even if $EV_c(t+2;a) > 0$ is weakened to $V_c(t+2;a) \geq 0$ because from $p_{t+1}\mu_{a+t1} \leq c$, it follows that $EV_c(t+2;a) = 0 \Rightarrow EV_c(t+1;a) = 0$.

Since we clearly have:

$$\mu_{t+1} > \delta EV_c(t+2;a),$$

the right-hand side of (20) decreases with p_{t+1}, so that (20) will be satisfied if p_{t+1} is small enough and $EV_c(t+2;a)$ is large. This implies that a must be small. Therefore, if a is close to zero, for any two consecutive, periods t and $t+1$, such that $\frac{p_{t+1}}{p_t}$ is greater than, but close to 1, and p_t is small, the hazard of termination decreases with t. Otherwise, the hazard of termination increases with t.

7.4 Proof of Proposition 5

For a given t, the hazard of first sale clearly decreases with a since the hazard of termination increases with a. For a given a, a change in the hazard of first sale between t and $t+1$ is given by:

$$\Delta_s = (1 - p_f(a+t+1))p_{t+1} - (1 - p_f(a+t))p_t.$$

If $p_f(a+t+1) \leq p_f(a+t)$, then Δ_s is clearly positive. Δ_s is negative only if $p_f(a+t+1)$ is sufficiently larger than $p_f(a+t)$. Therefore the relationship between p_f and Δ_s is generally ambiguous when p_f increases with t.

Table 1: Unconditional survival rates

Period	Abandon	First Sale	Right Censored	Surviving	Total
1	74	49	78	604	805
2	32	26	49	497	604
3	54	40	98	305	497
4	49	20	35	201	305
5	34	11	34	122	201
6	8	2	9	103	122
7	10	6	11	76	103
8	6	2	9	59	76
9	0	11	9	39	59
10	1	0	14	24	39
11	1	1	7	15	24
12			2	13	15
13			7	6	13
14			2	4	6
15			2	2	4
16			2	0	2
Totals	269	168	368	0	2875

Table 2: Age of patents at time of license

Age	Number	Percent	Cumulative Percentage
0	91	11.30	11.30
1	113	14.04	25.34
2	113	14.04	39.38
3	106	13.17	52.55
4	71	8.82	61.37
5	69	8.57	69.94
6	46	5.71	75.65
7	67	8.32	83.98
8	38	4.72	88.70
9	34	4.22	92.92
10	14	1.74	94.66
11	11	1.37	96.02
12	10	1.24	97.27
13	6	0.75	98.01
14	9	1.12	99.13
15	5	0.62	99.75
16	2	0.25	100.00
Total	**805**	**100.00**	

Table 3: Age of patents when events are observed

Patent Age	Termination	Commercialization	Right Censored	Total	Percent	Cumulative Percent
1	18	1	0	19	2.36%	2.36%
2	17	12	8	37	4.60%	6.96%
3	28	18	35	81	10.06%	17.02%
4	24	8	29	61	7.58%	24.60%
5	32	17	49	98	12.17%	36.77%
6	39	15	46	100	12.42%	49.19%
7	18	10	39	67	8.32%	57.52%
8	14	16	77	107	13.29%	70.81%
9	11	10	27	48	5.96%	76.77%
10	3	12	27	42	5.22%	81.99%
11	8	8	22	38	4.72%	86.71%
12	11	8	19	38	4.72%	91.43%
13	8	4	10	22	2.73%	94.16%
14	3	3	7	13	1.61%	95.78%
15	8	2	3	13	1.61%	97.39%
16	0	0	5	5	0.62%	98.01%
17	9	2	14	16	1.99%	100.00%
Total	**251**	**146**	**417**	**805**		

Table 4: Descriptive statistics

Variable	Mean	Std Dev	Min	Max
PATENT AGE	5.140	3.399	1	17
PATENT AGE^2	37.965	48.426	1	289
PATENT AGE^3	351.739	676.725	1	4913
Nature of Technology				
START-UP	0.327		0	1
PATENT SCOPE	1.339	0.639	1	6
PRIOR ART CITED	9.968	11.926	0	70
RADICALNESS	5.814	5.405	0	57
INDUSTRY FUNDED	0.168		0	1
GENERALITY	0.302	0.315	0	0.9
Technology classes				
DRUG PATENT	0.216		0	1
CHEMICAL PATENT	0.311		0	1
ELECTRIC PATENT	0.265		0	1
MECHANICAL PATENT	0.032		0	1
Appropriability Measures				
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
Period Dummies				
YEAR 1980-1984	0.257		0	1
YEAR 1985-1989	0.314		0	1

Table 5: Results using different methodologies

	Cox Proportional Hazards				Competing Risks with Independent Risks				Competing Risks with Unobserved Heterogeneity			
	(a1) Termination		(a2) First Sale		(b) Termination		First Sale		(c) Termination		First Sale	
NAME	**Hazard Ratio**	Z-Stat	**Hazard Ratio**	Z-Stat	**Parameter**	Z-Stat	**Parameter**	Z-Stat	Parameter	**Z-Stat**	Parameter	Z-Stat
PATENT AGE	**0.769**	-3.990	**1.208**	2.180	**-0.300**	-3.661	0.156	1.476	**-0.271**	**-2.579**	0.194	1.460
PATENT AGE^2	**1.013**	3.110	0.992	-1.380	**0.019**	4.030	-0.006	-0.983	**0.015**	**2.548**	-0.011	-1.401
Nature of Technology												
START-UP	1.230	1.510	1.101	0.530	0.048	0.282	0.193	0.957	**-1.197**	**-5.323**	-0.350	-1.311
PATENT SCOPE	0.943	-0.540	**1.345**	2.840	-0.092	-0.767	**0.277**	2.040	-0.079	-0.434	**0.492**	2.903
PRIOR ART CITED	1.002	0.180	0.982	-1.260	0.014	1.399	-0.017	-0.969	-0.015	-1.026	**-0.050**	-2.503
RADICALNESS	0.992	-0.450	1.021	0.820	-0.008	-0.507	0.026	0.959	0.028	0.994	**0.079**	2.342
INDUSTRY FUNDED	**0.658**	-2.080	1.069	0.290	-0.354	-1.578	-0.064	-0.232	**-0.609**	**-1.980**	-0.335	-0.952
GENERALITY	**1.881**	2.630	**0.427**	-2.900	0.029	0.105	**-0.642**	-2.192	-0.199	-0.530	-0.661	-1.613
Technology classes												
DRUG PATENT	0.867	-0.420	0.716	-0.740	-0.048	-0.117	-0.188	-0.337	0.097	0.139	-0.522	-0.725
CHEMICAL PATENT	1.091	0.360	**2.029**	2.120	0.158	0.602	0.676	1.943	0.149	0.407	0.299	0.692
ELECTRIC PATENT	0.826	-0.790	1.959	1.880	-0.166	-0.626	0.521	1.400	0.326	0.884	**1.465**	3.115
MECHANICAL PATENT	0.810	-0.480	0.832	-0.230	0.026	0.065	-0.112	-0.146	1.028	1.802	1.376	1.310
Appropriability Measures												
LEAD TIME	**2.389**	3.120	0.528	-1.850	**0.883**	3.331	-0.622	-1.606	0.161	0.435	**-1.136**	-2.141
SECRECY	**0.444**	-3.240	1.612	1.430	**-0.930**	-3.540	0.495	1.223	-0.856	**-2.272**	**1.082**	2.016
LEARNING	**0.461**	-2.560	**3.020**	2.580	**-0.723**	-2.380	**1.043**	2.099	0.053	0.127	**1.353**	2.113
PATENT STRENGTH	**0.589**	-3.250	**2.216**	3.030	**-0.710**	-3.805	**0.756**	2.388	-0.842	**-2.961**	**1.223**	3.108
Period Dummies												
YEAR 1980-1984	**0.276**	-2.160	1.662	1.210	0.061	0.231	-0.365	-1.640	0.415	1.120	-0.093	-0.330
YEAR 1985-1989	**0.630**	-2.440	1.393	1.590	**0.648**	3.397	**-1.147**	-4.307	0.503	1.850	**-1.781**	-5.577
α_{1i}					**-1.378**	-4.226	**-0.808**	-2.099	**-2.923**	**-3.590**	**-1.777**	-3.045
α_{2i}					**3.704**	5.712	**2.004**	2.770	**9.441**	**4.537**	**5.958**	4.482
θ_{1i}					**0.234**	2.871	**0.100**	2.334	0.002	1.521	0.001	1.220
θ_{2i}									1.087	1.474	0.305	1.816
q_i											**0.5430**	2.807
Failures	243		145		243		145		243		145	
# Licenses	805				805				805			
Time at risk (years)	2403				2403				2403			
Log Likelihood	-1459.19		-881.74		-1087.1454				-1055.5320			

Table 6: Competing risks model with unobserved heterogeneity

NAME	(a) Termination Parameter	(a) Termination Z-Stat	(a) First Sale Parameter	(a) First Sale Z-Stat	(b) Termination Parameter	(b) Termination Z-Stat	(b) First Sale Parameter	(b) First Sale Z-Stat	(c) Termination Parameter	(c) Termination Z-Stat	(c) First Sale Parameter	(c) First Sale Z-Stat	(d) Termination Parameter	(d) Termination Z-Stat	(d) First Sale Parameter	(d) First Sale Z-Stat
PATENT AGE	**-0.339**	-3.671	0.171	1.602	**-0.317**	-3.121	0.210	1.785	**-0.416**	-3.456	**0.323**	1.972	**-0.328**	-2.640	0.248	1.411
PATENT AGE^2	**0.016**	2.985	-0.010	-1.612	**0.016**	2.804	-0.011	-1.490	**0.016**	2.580	-0.012	-1.636	**0.012**	2.017	-0.012	-1.458
Nature of Technology																
START-UP	**-0.936**	-4.380	**-0.650**	-2.934	**-1.101**	-4.846	**-0.580**	-2.389	**-1.159**	-4.926	**-0.561**	-2.262	-1.263	-5.401	-0.351	-1.287
PATENT SCOPE	-0.167	-0.998	0.295	1.872	-0.079	-0.425	**0.423**	2.611	-0.107	-0.561	**0.421**	2.519	-0.126	-0.684	**0.510**	2.912
PRIOR ART CITED	-0.009	-0.805	**-0.045**	-2.727	-0.014	-1.033	-0.034	-1.835	-0.021	-1.411	-0.030	-1.555	-0.020	-1.364	**-0.048**	-2.299
RADICALNESS	0.032	1.515	**0.058**	2.014	0.018	0.648	0.034	1.109	0.025	0.829	0.031	0.981	0.035	1.163	**0.077**	2.184
INDUSTRY FUNDED	-0.531	-1.957	-0.080	-0.268	**-0.739**	-2.419	-0.162	-0.485	**-0.773**	-2.512	-0.187	-0.543	**-0.666**	-2.149	-0.350	-0.977
GENERALITY	-0.002	-0.005	-0.352	-1.061	0.047	0.131	**-0.935**	-2.469	0.028	0.077	**-0.948**	-2.469	-0.264	-0.677	-0.628	-1.494
Technology classes																
DRUG PATENT					0.152	0.214	-0.479	-0.683	-0.539	-0.554	0.707	0.589	-0.372	-0.381	-0.369	-0.303
CHEMICAL PATENT					0.185	0.493	0.556	1.372	-0.587	-1.010	1.409	1.627	-0.411	-0.705	0.838	0.940
ELECTRIC PATENT					0.270	0.734	**1.058**	2.662	-0.497	-0.943	1.734	1.861	-0.492	-0.938	1.950	1.956
MECHANICAL PATENT					1.040	1.825	1.189	1.215	1.038	1.045	0.665	0.228	1.124	1.218	0.690	0.233
Appropriability Measures																
LEAD TIME					0.243	0.634	**-1.006**	-1.991	0.430	1.106	-1.019	-1.838	0.371	0.982	**-1.176**	-2.023
SECRECY					**-0.879**	-2.273	0.522	0.997	**-0.981**	-2.554	0.557	0.999	**-0.995**	-2.630	**1.109**	1.977
LEARNING					-0.033	-0.078	**1.519**	2.400	-0.105	-0.248	**1.483**	2.267	-0.032	-0.077	**1.344**	2.039
PATENT STRENGTH					**-0.869**	-2.932	**0.932**	2.578	**-0.848**	-2.805	**0.974**	2.586	**-0.795**	-2.746	**1.207**	2.981
Interaction effects																
AGE*DRUGS									0.110	0.975	-0.155	-1.279	0.068	0.594	-0.010	-0.076
AGE*CHEM									0.145	1.600	-0.104	-0.937	0.110	1.252	-0.069	-0.568
AGE*ELEC									0.144	1.631	-0.066	-0.556	0.159	1.842	-0.059	-0.457
AGE*MECH									-0.076	-0.217	0.121	0.306	-0.082	-0.239	0.124	0.304
Period Dummies																
Y1980-1984													0.424	1.137	-0.143	-0.494
Y1984-1989													**0.560**	2.007	**-1.815**	-5.343
Log Likelihood	-1125.046				-1082.583				-1077.486				-1051.264			

Table 7: Robustness of quadratic form

NAME	(a) First Sale Parameter	(a) First Sale **Z-Stat**	(b) First Sale Parameter	(b) First Sale **Z-Stat**	(c) Termination Parameter	(c) Termination Z-Stat	(d) Termination Parameter	(d) Termination **Z-Stat**
PATENT AGE	-0.007	-0.022	0.015	0.460	0.310	1.253	-0.026	-0.799
PATENT AGE^2	0.017	0.420			**-0.074**	-2.097		
PATENT AGE^3	-0.001	-0.699			**0.004**	2.541		
Log Likelihood	-1055.229		-1057.102		-1051.396		-1058.392	

Notes: In these regressions, we include patent quality controls, field dummies and appropriability measures, similar to regression 5c. For clarity, only the relevant hazard coefficients are reported. In each unreported hazard, age is assumed to follow a quadratic form. Statistically significant coefficients appear in bold.

Figure 1: Conditional probability of failure

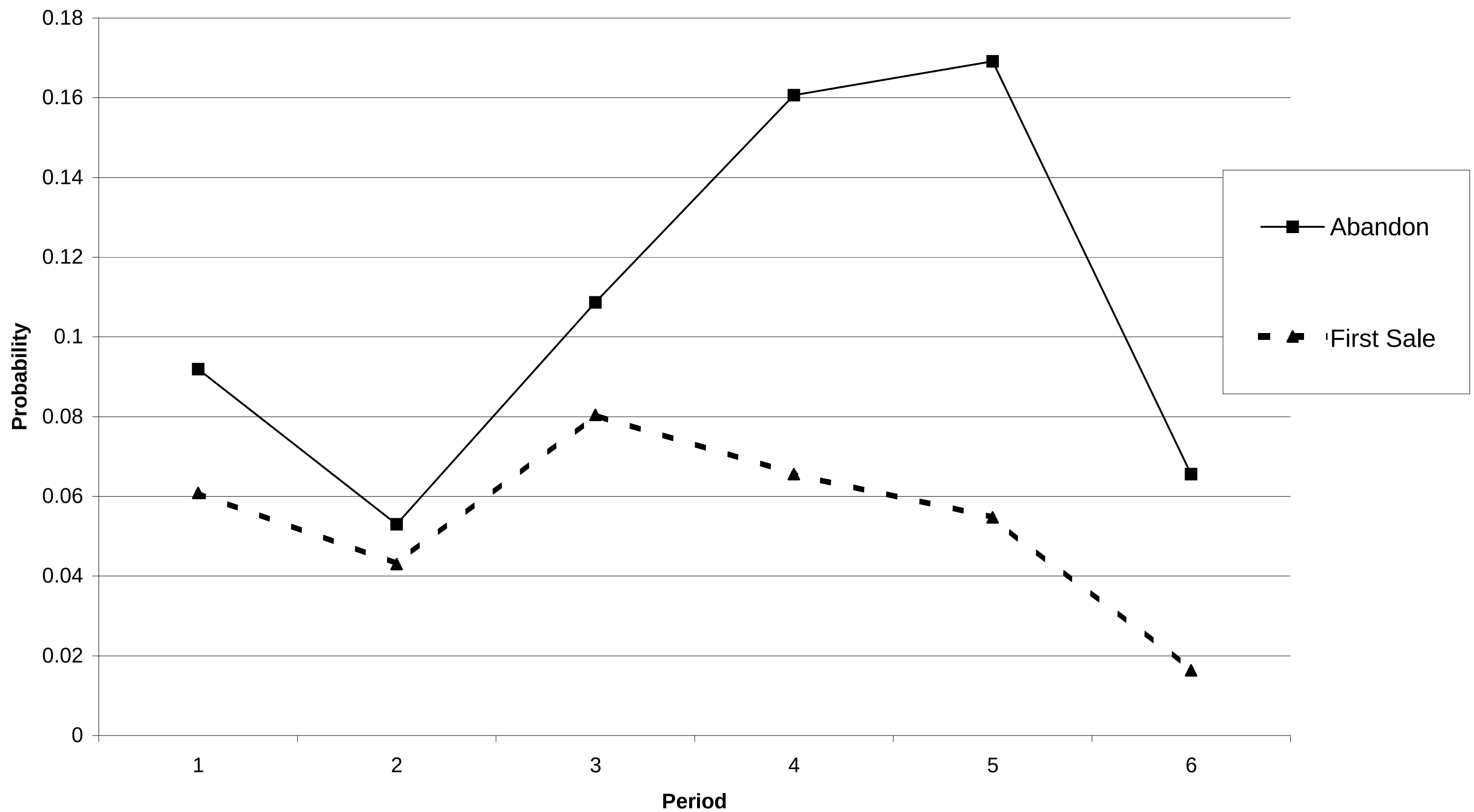

Figure 2: Change in hazard of termination with patent age

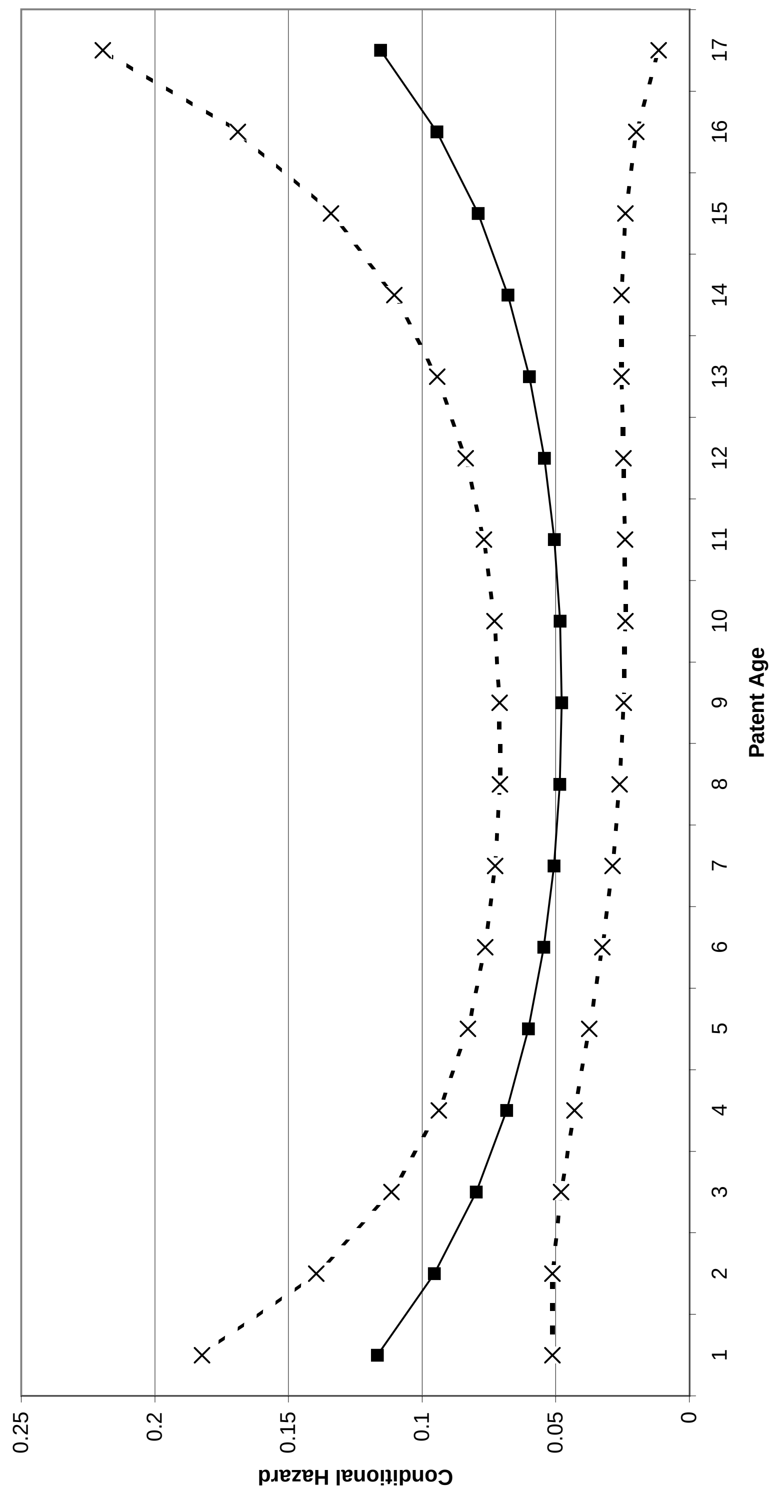

Figure 3: Change in hazard of first sale with patent age