Appropriability and the timing of innovation: Evidence from MIT inventions[1]

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Abstract

A key principle underlying the Bayh-Dole Act is that strong property rights are needed for firms to invest in commercializing university inventions, many of which require substantial further development at the time they are licensed exclusively. In this paper, we exploit a database of 803 attempts by private firms to commercialize inventions licensed 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 commercial 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 also find support for the view that appropriability of returns is negatively related to the hazard of termination.

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.[1] 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 on both sides of the debate, there has been surprisingly little scholarly 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? Some observers believe that 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 a 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 most avid proponents of Bayh-Dole argue that because commercial application of university inventions usually requires substantial additional development, private firms will not make the necessary investment unless they can

[1] 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 $665Mil.

appropriate the returns to that investment. For example, a recent survey of sixty-two U.S. university technology transfer offices provides evidence that the majority of inventions licensed are so embryonic that commercial use requires substantial further development, and that, for three-fourths of the inventions, 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 profits, 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 the firm's decision to develop an invention.

In this paper, we exploit a unique database that allows us to address directly the issue of whether private firms adopt and commercialize university inventions in the absence of strong property rights to the inventions. We examine the population of 803 attempts by private sector firms to commercialize inventions assigned to the Massachusetts Institute of Technology and licensed by the institution between 1980 and 1996. We use information obtained from the MIT technology licensing office to identify the dates of patenting and of the license of patented inventions and 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 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 as time elapses since the probability that development will yield a commercially viable product increases.

In Section 2, we present a model that allows us to examine these two opposing dimensions of time - length of remaining patent protection and effect of time on the probability of successful commercialization. To focus on these two effects, we adopt 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, so that, if successful, the firm sells its new products immediately. Because of the opposing effects of length of remaining patent protection and effect of time on the probability of technical success, we can find increasing or decreasing hazard rates for the date of termination. We provide conditions on the probability of technical success for which there is an inverted u-shaped hazard of first sale and a u-shaped hazard of termination.

In sections 3 and 4, we present the data and empirical results for competing risk regression models to predict the hazard of first sale and license termination for 803 attempts to commercialize MIT-assigned patents licensed exclusively between 1980 and 1996. Consistent with our model, we find that the hazard of first sale has an inverted u-shaped relationship with the age of the patent and the hazard of license termination has a u-shaped relationship with the age of the patent. Our results are robust to controlling for several measures of the appropriability of the invention, the general technical field in which the invention is found, and the source of funding for the invention.

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, π^m, per period until the patent expires, which occurs at $T \geq 2$. To successfully commercialize the invention, the firm must invest c per period. We abstract from whether this running development cost reflects internal costs or payments to the university, such as minimum royalties, sponsored research and/or consulting for inventor assistance.[2]

The returns to the firm from investing in further development are uncertain for both technical and market reasons. In a recent survey of businesses that license-in university inventions, Thursby and Thursby (2002) found that 46% of all inventions

[2]Note that the details of the license contract are fixed in this problem. Upfront fees are sunk and do not enter the problem, while minimum royalties affect the firm's decision through c and running royalties are an element of π^m.

licensed fail and of these 47% failed 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 incorporate both technical and market uncertainty in the following way.[3] Let the probability that the firm will be successful in its attempt to develop a commercially viable product be $p(t) \in [0, 1)$. 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 as it surely does not decrease the probability.[4] If the invention is a technical success at period t, the firm receives a profit equal to $\pi^m(\tilde{\epsilon}_t)$ each period until the patent expires, where $\tilde{\epsilon}_t$ is a continuous random variable with a distribution that is time invariant. Note that if the realization of $\tilde{\epsilon}$ in period t is equal to x, and success occurs in that period, then the firm receives $\pi^m(x)$ until the patent expires. Because the value for selling any product based on the invention becomes zero when the patent expires and the distribution of shocks to the market is stationary, the firm will sell as soon as technical success occurs.

Now suppose the firm has neither succeeded nor decided to stop investing by period t, we assume the firm observes the shock and then makes a decision either to continue (i.e., to invest c) or to terminate the project. This is an optimal stopping problem similar to that analyzed by Roberts and Weitzman (1981).[5] Simply put,

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

[4]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.

[5]Our model is similar to their sequential decision process. While their analysis is more general than ours, it does not allow for a characterization of the hazard of first sale as they do not separate expected benefits into the value of selling and the probability of first sale. Kamien and Schwartz (1971) and Grossman and Shapiro (1986) examine similar problems under various assumptions about the probability of success. However, they assume the value of investing is positive throughout so that termination is not an issue.

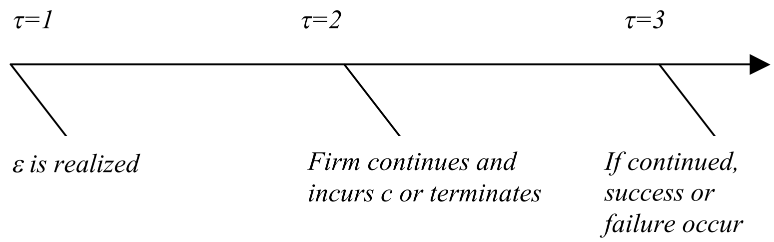

Figure 1: Sequence of decisions and events within any period t.

after the firm has observed the shock for the current period, its optimal decision rule is to continue in any period with a positive continuation value and stop as soon as the continuation value becomes zero.[6]

In general, if $\tilde{\epsilon}_t = \epsilon_t$, the (realized) value from selling at t will be simply:

$$V_s(t, \epsilon_t) = \sum_{n=0}^{T-t} \delta^n \pi^m(\epsilon_t) = \frac{(1-\delta^{T-t+1})\pi^m(\epsilon_t)}{1-\delta}, \tag{1}$$

where $\delta \equiv \frac{1}{1+r}$ is the discount factor. Note that there is no ˜ on ϵ_t, because we assume that the firm observes ϵ before it makes the decision whether to continue or not. Thus ϵ denotes the realized value of the random variable $\tilde{\epsilon}$. For fixed ϵ, $V_s(t, \epsilon) \equiv V_s(t)$.[7]

The value of continuing at any t can be written as:

$$V_c(t, \epsilon_t) = \max\{-c + p(t)V_s(t, \epsilon_t) + B(t), 0\}, \tag{2}$$

where we defined:

$$B(t) \equiv \delta E \sum_{n=0}^{T-t-1} \delta^n \prod_{i=0}^{n} (1 - p(t+i))(p(t+n+1)V_s(t+n+1, \tilde{\epsilon}_{t+n+1}) - c).$$

In (2), we refer to the term $p(t)V_s(t, \epsilon_t)$ for any given ϵ_t as the "probabilistic value of selling." As we will see in the next sections, the way the probabilistic value of selling changes from period to period will have important implications for the timing of

[6] See Ross (1983) for a general treatment of bandit processes. Similar problems in economics have been examined by Jensen (2002).

[7] Since V_s is linear in π^m, this notation also applies to $EV_s(t, \tilde{\epsilon})$.

innovation. This is not surprising since this term incorporates all of the uncertainty and time sensitivity associated with the innovation: the chance that it will be a technical success ($p(t)$), the per-period profit level ($\pi^m(\epsilon_t)$), the discount factor and the patent length. In the remainder of this section, we characterize the hazard of terminating and the hazard of first sale.

2.1 The hazard of terminating

Let $\hat{\epsilon}_t$ be that value of ϵ_t such that $V_c(t, \hat{\epsilon}_t) = 0$. Since $V_c(t, \epsilon_t)$ is increasing in ϵ_t, the probability of terminating at a certain date t is given by:

$$p_f(t) = \Pr(V_c(t) = 0) = \Pr(\tilde{\epsilon}_t \leq \hat{\epsilon}_t),$$

where f stands for "failure." The hazard of termination at t is defined in terms of this probability, and is given by:

$$h_f(t) = \frac{p_f(t)}{\prod_{n=0}^{t-1}(1 - p_f(n))}. \tag{3}$$

Note that the sign of a change in $h_f(t)$ between t and $t+1$ is the same as the sign of $p_f(t+1) - p_f(t) + p_f(t)^2$. Thus, the hazard of terminating increases between t and $t+1$ whenever the probability of failure (i.e., termination) increases. On the other hand, in order for the hazard of terminating to decrease for some t, either the probability of terminating has to decrease by a large amount so as to offset the squared term effect, or $p_f(t)$ has to be small, so that the squared term is itself small.

Characterizing the hazard of terminating fully is a difficult task since it involves $p_f(t)$ as defined by $\Pr(V_c(t) = 0)$, where V_c is given by (2). We study the sign of a change in the hazard rate, and in order to do so, break the analysis of a change in V_c into two parts: a change in $p(t)V_s$ for a given ϵ and a change in $B(t)$.

We need to examine equation (2). We first study a change in $p(n)V_s(n)$, for a given ϵ between n and $n+1$, which amounts to the following:

$$p(n+1)V_s(n+1) - p(n)V_s(n). \tag{4}$$

Note that such a change is negative in the special case where $p(t) \equiv p$. In the more general case where the probability of technical success is a non-trivial function of time, whether or not (4) is positive depends on whether the probability increases or decreases with time, as well as the rate of change in that probability across periods. A change in $B(n)$between n and $n+1$ is given by:

$$-E[(1-p(n))(p(n+1)V_s(n+1,\tilde{\epsilon}_{n+1})-c)]+[1-\delta(1-p(n))]B(n+1). \qquad (5)$$

In the remainder, we let $E[\pi^m(\tilde{\epsilon}_t)] = \mu_t \equiv \mu$. Note that even assuming the probability of technical success increases does not ensure that $p(t)V_s(t,\epsilon)$ increases since $V_s(t,\epsilon)$ decreases for a given ϵ. Nonetheless, it is true that a higher μ decreases the probability of termination at every t. This can be seen by looking at (2) and noting that, all else equal, the value of continuing increases with μ. This, of course, reflects the fact that a higher average monopoly profit increases the incentives for the firm to pursue the project. We consider three cases of interest.

2.1.1 Case I

In this sub-section, we consider the case where the increase in the probability of technical success is more than offset by the decrease in the value of selling as t approaches T. That is, we assume:

A1: For every t and every given ϵ, $p(t)V_s(t,\epsilon)$ decreases with time.

Note that concavity of the probability function in time is neither necessary, nor sufficient for this assumption to hold. However, for a given rate of decrease in the value of selling, the more concave that probability, the more likely it is that the assumption will be satisfied. This case is of interest because even if for some R&D projects, it is reasonable to assume that the probability of technical success increases over time, it is, again, not sufficient to guarantee that the "probabilistic value from selling" $(p(t)V_s(t))$ increases with time. The implication of this assumption is presented in proposition 1. Given assumption A1, combined with the fact that $p(t)$ is non-decreasing, we obtain the following result:

Proposition 1 *Assume A1. $h_f(t)$ increases with time.*

Proof. Consider a change in (2). The second term decreases with time by assumption A1 and a change in the third term is given by (5). Suppose (5) is non-positive, then:

$$B(t+1) \leq \frac{(1-p(t))\sum_{n=0}^{T-t-1}[\delta(1-p(t)]^n(p(t+1)V_s(t+1)-c)}{1-[\delta(1-p(t))]^{T-t}}. \tag{6}$$

But this is always true under A1. Therefore $p_f(t+1) > p_f(t)$, which is sufficient for $h_f(t+1) > h_f(t)$. Since t was arbitrary, the result holds in general. □

Proposition 1 implies that if the firm is patient (δ is high), then the discounted value from selling decreases so quickly, that even if the probability of technical success increases, it becomes more and more likely that the firm will terminate as time passes. In other words, if the discount factor is large enough, a strictly increasing probability of success may coexist with a strictly increasing hazard of termination. This is because as time passes the discounted sum of profits from sale from the period of first sale to the patent expiration period becomes smaller, an effect accentuated by a large δ for patient firms.

In terms of the way the discount factor affects the size of the hazard of termination, differentiating (2) yields[8]:

$$\frac{\mathrm{d}V_c(t)}{\mathrm{d}\delta} = p(t)\frac{\partial V_s(t)}{\partial \delta} + \delta(\sum_{n=0}^{T-t-1}\prod_{i=0}^{n}(1-p(t+n+i)) \times$$
$$E[n\delta^{n-1}(p(t+n+1)V_s(t+n+1)-c) + \delta^n p(t+n+1)\frac{\partial V_s(t+n+1)}{\partial \delta}]) > 0.$$

This shows that more patient firms are less likely to terminate at any period t. An empirical implication may be that firms facing tight cash constraints will have higher hazards of termination at every period t.

2.1.2 Case II

Suppose that instead of being non-positive, (4) is increasing for small values of t, and non-positive for large values of t. More formally,

A2: There exists $\hat{t}$ such that for every $t < \hat{t}$ (resp. $t \geq \hat{t}$), and for every given ϵ, $p(t)V_s(t,\epsilon)$ increases (resp. decreases) with t.

[8] For a given ϵ, which we suppress as an argument, such that $V_c(t,\epsilon) > 0$.

Consider first those periods before $\hat{t}$, in which case the expression in (4) is positive. Using the expression for the value of selling in equation (1), it is straightforward to show that in order for the probabilistic value of selling to increase, the probability that development will yield a technical success must increase at the beginning of the patent life.[9] That is, if t is strictly less than $\hat{t}$, A1 is exactly equivalent to:

$$p(t+1) \geq \left(\frac{1-\delta^{T-t+1}}{1-\delta^{T-t}} \right) p(t). \tag{7}$$

This also implies $p(t) \geq \left(\frac{1-\delta^{T+1}}{1-\delta^{T-t}} \right) p(0)$ for $t < \hat{t}$, which, for given discount factor and patent length, is more likely to be satisfied if $p(0)$ is small. Moreover, a short patent length enhances the effect of the term multiplied by $p(0)$ in this condition. So the lower the patent length, the lower $p(0)$ needs to be for this condition to be satisfied. On the other hand, as patent length becomes very large, the term multiplied by $p(0)$ goes to 1 such that the inequality is always strictly satisfied (the same is true of (7)). [10] In other words, with a non-decreasing probability of technical success, the probabilistic value of selling will increase initially for all inventions with a strong patent position in terms of patent length (T large). However, for inventions with a short patent length (T small), the probabilistic value of selling will initially increase only for those whose probability of technical success is initially quite small. Finally, inventions that do not satisfy any of these criteria will have strictly decreasing probabilistic values of selling and increasing hazards of termination, as illustrated by proposition 1.

Proposition 2 *Assume A2 and $p(0) \to 0$. Then there exists $\hat{n}$, $0 < \hat{n} < \hat{t}$, such that if $t \leq \hat{n}$, then $p_f(t)$ decreases with time.*

[9] While convexity of $p(t)$ is neither necessary, nor sufficient for A2, we can show that if the value of selling times the probability of technical success increases, and the probability of success is convex, then the value of selling times the probability of technical success is also convex. Intuitively, this suggests that innovations for which age of the patent positively affects not only the probability of technical success, but also the rate at which it grows, always become increasingly more profitable in expected value terms as patent age increases.

[10] Assume that $T = 20$ and $\delta = 0.9$, then if $p(0) = 0.05$, the assumption is satisfied if $p(1) \geq 0.0507$, $p(2) \geq 0.0515$, $p(3) \geq 0.0524$, etc... In the data, the average empirical probability of first-sale for the first six periods is about 0.05 (see figure 1).

Proof. Consider a change in the expected value of (2) between t and $t+1$. Using (5) this amounts to:

$$p(t+1)V_s(t+1) - c - (p(t)V_s(t) - c) - (1-p(t))(p(t+1)V_s(t+1) - c)$$
$$+[1-\delta(1-p(t))]B(t+1).$$

Re-arranging, we obtain:

$$p(t)[p(t+1)V_s(t+1) - V_s(t)] + cp(n)(1-p(t+1)) + [1-\delta(1-p(t))]B(t+1),$$

Evaluating at $t=0$ and taking the limit as $p(0)$ goes to zero, we are left with only one positive term, $(1-\delta)B(1)$. Note that if $B(1)$ were negative, then $B(0)$ would be as well, by A2, so that the project would have a negative expected present value at 0, and the firm would not consider undertaking it. □

To see the intuition behind this result and the way it depends on A2, notice that if $p(t)V_s(t) - c$ is very low in early periods, but $p(t)V_s(t)$ increases, the better outcomes must be in later periods. The closer the firm gets to these outcomes, the less likely it is that the firm will terminate. Note that this constitutes a necessary, but not sufficient, condition for the hazard of terminating to decrease over that period of time. A sufficient condition would be that the probability of terminating be low between 0 and $\hat{n}$, in order for the squared term in the expression of a change in the hazard rate to be negligible. The additional assumption in proposition 2, which necessitates that $p(0)$ be very low at the beginning of time is consistent with assumption A2 being satisfied, as we discussed above.

Now consider the shape of the hazard function for $t \geq \hat{t}$. For these periods, the value of selling times the probability of selling goes down, for a given ϵ. With this assumption, we should expect to see the hazard of terminating go up. This is exactly the result that we obtained in proposition 1 in the previous section. The second part of A2 implies an increasing unconditional probability of termination for every $t \geq \hat{t}$, and therefore, and increasing hazard of termination.

If A2 does not hold, it is difficult to draw conclusions as to the shape of the hazard rate function for small values of t. In this case, for $t < \hat{t}$, the countervailing effects may or may not offset each other. However, we have shown in proposition 2 that for small probabilities of success at the beginning of the project's life, then a necessary condition for the hazard of terminating to decrease with time is satisfied. The effect of the discount factor on the direction of change of the hazard of termination is such that, other things equal, a patient firm (i.e., δ higher) will reach its "turning point" $\hat{t}$ sooner than an impatient firm. This will shift the minimum value of the hazard of termination to the left on the timeline. The effect on the value of continuing *per se* is identical to the effect described in the previous section. A patient firm will have a lower hazard of termination than an impatient firm at each point in time.

To summarize, R&D projects with the characteristics in A2, as well as the characteristics implied by the additional assumptions in the statement of the propositions, are likely to generate u-shaped hazards of termination and hazards of first-sale with an inverted u-shape.

2.1.3 Case III

Finally, consider the case in which the probability of selling increases enough over time so that it offsets the decrease in the value of selling every period. That is, we assume:

A3: For every t and every given ϵ, $p(t)V_s(t,\epsilon)$ increases with time.

A3 is equivalent to $\frac{p(t+1)}{p(t)} \geq \frac{1-\delta^{T-t+1}}{1-\delta^{T-t}}$ and implies $\frac{p(t+i)}{p(t)} \geq \frac{1-\delta^{T-t+1}}{1-\delta^{T-t-i+1}}$ for every $i > 0$. Therefore, for T large enough, the fact that $p(t)$ is non-decreasing will imply A3, at least in early periods (i.e., t close to zero). From proposition 2, and with A3, we know that there will exist $\hat{n}$ such that the probability of terminating decreases between periods 0 and $\hat{n}$. On the other hand, we can no longer apply proposition 1 for subsequent periods since $p(t)V_s(t)$ increases over time until the patent expires, and we are left with indeterminacy as discussed at the end of the previous section.

Consider the case in which $p(0)V_s(0) > c$, so that the average value of selling is greater than the per-period cost at all times. Manipulating and rewriting (5), a change in $B(t)$ will be positive if, and only if:

$$\sum_{n=0}^{T-t} \delta^n \left(\prod_{i=0}^{n}(1-p(t+1+i))\right)\left(\frac{p(t+2+n)(1-\delta^{T-n-1})\mu}{1-\delta} - c\right)$$
$$- \sum_{n=0}^{T-t} \delta^n (1-p(t))^{n+1}\left(\frac{p(n+1)(1-\delta^{T-t})\mu}{1-\delta} - c\right)$$

$$\geq \quad [\delta(1-p(t))]^{T-t+1} \sum_{n=0}^{T-t} \delta^n (1-p(t))^{n+1} \left(\frac{p(n+1)(1-\delta^{T-t})\mu}{1-\delta} - c \right). \quad (8)$$

Taking the limit on both sides of the inequality as T goes to infinity, we note that the term on the right-hand side goes to zero.[11] The left hand-side is bounded as well, but may converge to a term that is either positive or negative. However, since $p(n)$ increases with n, the fact that T is large implies that A3 will be easily satisfied even if the probability of selling does not increase quickly in early periods. Therefore it is more likely that (8) will be satisfied in early periods, when $(1-p(n))$ does not fall too quickly. If (8) is non-negative for any t, then, under A3, the probability of terminating decreases between t and $t+1$.

The intuition behind this result is simply that if the probability of selling does not increase very much from period to period, then the better outcomes are far in the future. If in period 0, it is better to continue for a given ϵ, then it will be preferable to continue as well in later periods when the better outcomes are discounted less strongly. On the other hand, as the firm gets closer to the last period, the cumulative value that it gets in the event of a failure (B) becomes less attractive and tends to pull the value of continuing down. However, since the event of a success is more imminent with time, the possibility that the hazard of terminating decreases throughout patent life cannot be excluded.

2.2 The hazard of first sale

In this section, we will see that propositions 1 and 2 have interesting and intuitive implications as to the effect of the probability of technical success and the probability of terminating on the shape of the hazard of first sale as well.

But first, we define the hazard of first sale. In our model, we assume that the firm learns market conditions (ϵ), before it makes the decision to incur the cost of development and has a chance to commercialize the innovation. If the firm terminates, it

[11] The sum is definitely bounded, since it can be viewed as the product of two sequences, one of which monotone and converging to zero. Applying Dirichlet's test, we get the result. Now, the term that is multiplied to the sum obviously goes to zero. Even if $p(t)$ is low, it does not take a very large T for $[(1-p(t))\delta]^{T-t+1}$ to go to zero. For example, set $\delta = 0.9$, $p(0) = 0.1$, then if $T = 30$, that term is equal to 0.00015. If $p(10) = 0.3$, then it is equal to 0.0000061.

will never commercialize. Thus, the event “first sale” combines the two events that the firm continues and that development yields a product that can be sold. For this reason, the probability of first sale at any period t is: $q(t) \equiv (1 - p_f(t))p(t)$ Note that we treat termination and technological success as independent events.[12] Hence the hazard of first sale is the following:

$$h_s(t) = \frac{q(t)}{\prod_{n=0}^{t-1}(1 - q(n))}. \tag{9}$$

From the definition of the probability of first sale, we see that the hazard of first sale depends critically on the probability of termination. Consequently, there exists a very close relationship between the hazard of first sale and the hazard of termination.

In the same way as for the hazard of terminating, we are interested in a change in (9) between t and $t + 1$. This will be of the same sign as $q(t + 1) - q(t) + q(t)^2$. Hence using the fact that $p(t)$ is non-decreasing, we obtain immediately that the hazard of first sale will increase whenever the probability of termination, p_f, decreases. Combining the first part of A2 and proposition 2, this implies that for every $0 \leq t \leq \hat{n}$, the hazard of first sale increases. However, using the second part of A2 in combination with proposition 1, it is still possible for the firm to experience periods during which the hazard of termination increases, but the hazard of first sale increases. The main reason for this pattern is that a decreasing unconditional probability of first sale is necessary but not sufficient for the hazard of first sale to decrease. Moreover, given an increasing probability of technical success, the only factor that may drive the hazard of first sale down is a sharply rising probability of termination.

Our theoretical analysis therefore suggests that given a non-decreasing probability of technical success over time, if assumption A1 is satisfied, the hazard of termination reaches a minimum while the hazard of first sale is still upward-sloping. As we shall see, we find this result in our empirical analysis as well. This stresses the tension between development and the existence of a protected market for the innovation. By waiting, the firm increases its chance of technical success, but sees the potential

[12]This would not be the case under other timing assumptions. For example, if the firm knew development was going to be successful at the beginning of the period, it could condition the decision to continue. In our case, however, the firm makes the decision to continue before it knows whether the invention will be a technical success or not, i.e. based on the expectation of profit.

profit from sales decrease. The "market effect" (decreasing $V_s(t)$ for every given ϵ) becomes stronger in later periods where each period of missed sales represents a greater percentage of the remaining expected present value of profits, possibly leading to shapes of the hazards of termination and first sale like those described in sub-sections 2.1.2 and 2.2.

3 Data

The data used to test the model's predictions were collected from the Technology Licensing Office 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 during 1980-1996 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. We begin the observation of the licensing of a patent in the year that MIT TLO records indicate that a licensing agreement by a given firm was first established for that 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. 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. Table 1: shows descriptive statistics for our analysis. 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. Lerner's (Lerner (1994)) measure of PATENT SCOPE is based upon the number of international patent classifications found on the patent. Lerner 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. PRIOR ART CITED measures the number of prior patents cited by the focal patent. It is hypothesized that an increase in prior art is associated with less novel knowledge. In addition, an increase in prior art narrows the scope of the property rights covered by the focal patent. APPROPRIABILTY is a measure from the Yale survey on innovation (Levin et al. (1985); Levin et al. (1987)). This measure is the maximum score on a seven point Likert scale to six different mechanisms used to appropriate the returns to innovation for process or product R&D for a line of business.[13] We include several additional control variables in the hazard predictions. These variables are all designed to control for the commercial quality of the invention. 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 should increase the likelihood of termination. It is unclear, however, how this should influence the likelihood of first sale. On one hand uncertainties associated with establishing a new firm may reduce the likelihood of first sale. However, new firms may have stronger incentives to commercialize as their survival depends upon successful commercialization.

Second, we include a dummy variable that take 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.

[13]The mechanisms were patents prevent duplication; patents secure royalty income, secrecy, lead time, moving down the learning curve, complementary sales and service efforts.

Third, 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 that previous patents cited on the focal patent are found, but the patent itself is not in. We expect more radical patents will have a higher hazard of TERMINATION and a lower hazard of COMMERCIALIZATION because radical technologies are more difficult to develop.

Our theoretical model describes exclusive licenses; therefore our empirical analysis explores exclusive licenses only. The decision to license exclusively is clearly endogenous to the type of technology and market conditions. By conditioning the analysis on the choice of an exclusive license we increase the parallel between the theoretical model and the empirical analysis. There are 803 exclusive attempts corresponding to 2875 observations.[14]

It is, of course, plausible and likely that licenses are terminated after commercialization. However, the MIT licensing office reports that this is a rare event, and hence this information was not collected. That is, we only ever observe the first event that occurs. The analysis below predicts the likelihood of the first event.

Table 2 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 (269 terminations vs. 168 successes). The table also suggests that uncertainty associated with an innovation is generally resolved in the first 5 years of license. Figure 1 reports the conditional probabilities of a license of a patent being terminated or commercialized. Whereas the conditional probability of first sale remains constant, the probability of termination peaks in years 4 and 5. Note that from the 6th year on the conditional probabilities are based upon small samples. Hence, in the duration analysis below we assume one baseline hazard for any event after year 5.

The data can be broken down into four broad technological categories, drugs,

[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. It appears that economic theory about licensing does not have a good sense of this empirical reality. It assumes that there is a strict dichotomy between exclusive and non-exclusive licenses where in reality everything is exclusive with variation on the negotiated size of the exclusive right.

electronics, chemicals and other (including mechanical). Figure 2 compares the termination patterns in the various categories and suggests that termination patterns are distinct. For example, licenses of drug patents tend to survive longer than other types of inventions. The empirical hazard rates to first sale are similar to those to termination.

4 Empirical Results

Our theoretical model suggests that attempts are either commercialized, in which case we observe a first sale, are terminated by the licensee, 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 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 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) is 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. 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:

$$\Pr(T_d = k|X, T > k-1) = 1 - \exp(-\exp(\alpha_{dk} + \beta_d' x)), \tag{10}$$

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

$$\Pr(T_f = k|X, T > k-1) = 1 - \exp(-\exp(\alpha_{fk} + \beta_f' x)), \tag{11}$$

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:

$$S(k_s, k_d|x) = \exp\left(-\sum_{r=1}^{k_f}\exp(\alpha_{fk} + \beta_f' x) - \sum_{r=1}^{k_d}\exp(\alpha_{dk} + \beta_d' x)\right). \tag{12}$$

Both events are assumed independent. 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 $w \in \{f, d\}$. The vectors of parameters β_w represent possibly time varying effects of the exogenous variables. However, in the current specification the effects are assumed to be constant over time. Define

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

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, $0.5[S(k-1, k-1) + S(k, k) - S(k-1, k) - S(k, k-1)]$ is made because durations are measured in discrete time. The log-likelihood is:

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

for each of the K_n periods of each of the N attempts.[15]

To identify the model, it is necessary to fix the baseline hazards α_{f0} and α_{d0} and they are fixed at the mean hazard at all periods.

[15]Two problems are immediately apparent. First, because the regressors are time-variant, we do not observe the x vector in period 0. Hence, the first period is dropped from our regressions. Note that if we assumed that the regressors were time invariant, or used the mean values of across all

We find evidence that supports assumption A2 according to the predictions of the theoretical model. Our regressions robustly predict that the hazard of first sale has an inverse "U" shape in patent age while the hazard of termination has a "U" shape in patent age. We find that the results are sensitive to the inclusion of the APPROPRIABILITY variable. Although the u-shaped result is robust, without this variable the data do not attribute the inverse u-shape to first sale and the u-shape to termination.

We begin with a discussion of regression (i). The regression reports an increasing hazard of first sale which eventually decreases and an opposite pattern for termination. The χ^2 test that AGE and AGE SQUARED are jointly zero in the commercialization equation is rejected ($\chi^2 - stat = 14.69$). Similarly, the χ^2 test that the technological category dummies are jointly zero is rejected ($\chi^2 - stat = 8.66$). To demonstrate the size of these effects, we report the mean predicted hazard for all inventions at various simulated patent ages. The results are described in Figure 3. As we can see, increasing the age by one year for a patent of mean age (6.71) increases the hazard probability of first sale by 0.002 (since the mean predicted hazard of 6.7 year old patent is 0.014; this implies a 15% increase in the predicted hazard). The effect begins to reverse itself after 15 years. However, this statement is based upon the small number of older patents in our sample. Patents are more likely to be commercialized if they span more international patent categories. If each sample patent had spanned one additional category, the mean increase in the conditional hazard of first sale would be 0.008, which is a 38% increase in the hazard. Patents are less likely to be commercialized if the methods of appropriating the innovation are stronger. Each scale score increase of one reduces the hazard of first sale by 0.01, which is equivalent to a 50% change in the predicted hazard rate.

Licenses of patents are less likely to be terminated as they age, and this likelihood increases at a certain point, although weakly. The χ^2 test that AGE and AGE SQUARED are jointly zero is rejected only at the 90% level ($\chi^2 - stat = 4.94$). However, the χ^2 test that the technological category dummies are jointly zero is not

periods for each licensed patent, we could include this period. Two additional shortcomings are the assumption that the events (first sale and drop) are independent and the fact that the regression does not account for heterogeneity of the inventions. These two problems are solved together and will be included in future drafts.

rejected ($\chi^2 - stat = 2.63$). The mean predicted hazard for all inventions at various simulated patent ages is reported in Figure 3. As we can see, increasing the age by one year for a patent of mean age (6.71 years) increases the hazard probability of termination by 0.001, or 15%. The effect is larger for younger patents. As a patent ages from one year to two the hazard of termination decreases on average 0.003 which is a 12.5% decrease in the mean predicted probability. The hazard of termination decreases as patents become more appropriable. Each one scale score increase in appropriability decreases the predicted hazard of termination by 0.007, which is a 40% decrease from the baseline hazard. As we would expect, licenses of innovations stemming from industry funded research are less likely to be terminated, whereas a patent commercialized through a startup is much more likely to be terminated. On average, the predicted increase in hazard of termination of a license of a patent stemming from research funded by industry is 0.006 if it were not funded by industry. This reflects a 50the experiment we find that the predicted hazard of termination of patents not funded by industry decreases 0.005 or 50hazard of termination of patents licensed to startups decreases 0.006, or 54licensed to established firms, all else being equal. If patents licensed to established firms were licensed to startups, the predicted hazard of termination increases, on average 0.007, or 64

The robustness of these results to changes in specification are explored in regressions (ii)-(v). Importantly, we see that exclusion of the APPROPRIABILITY variable results in a sign reversal in the termination equation for the coefficients of AGE and AGE-SQUARED in the termination equation. In this regression, these coefficients are now significant. Although not directly evident from regression (iv), in unreported regressions we found that in order to reverse the signs of patent age coefficients it was sufficient to drop APPROPRIABILITY alone. Hence, without this variable, AGE and AGE-SQUARED are picking up the fact that more appropriable innovations are less likely to be abandoned. At present, because of the aggregate nature of the appropriability measure, it is difficult to interpret this result, except to say that the economic decisions are clearly related to the effectiveness of patent protection. We expect to unpack this measure so as to understand how the effectiveness of different the mechanisms summarized in the APPROPRIABILITY variable affect both the decision to abandon and commercialization success.

5 Conclusions

In the two decades since the passage of the Bayh-Dole Act, university patent licensing has grown steadily. Many researchers and policy makers cite the passage of the Act as facilitating the commercialization of university inventions. However, others have rightly pointed out that the Act may not have mattered at all. The trend toward licensing might have occurred anyway.

Our study sought to provide some scholarly analysis to question whether firms would adopt and commercialize university inventions in the absence of strong property rights to the inventions. We developed a model that examines the decision of a firm that has licensed a university invention whether to invest in further development or to terminate the project. Our model showed that stronger appropriability conditions as measured by time to patent expiration increase the likelihood that the firm will invest in further development. We also show that, in general, the hazard of termination and first sale can have any pattern. Nonetheless, we find a u-shaped hazard of termination and inverse u-shaped hazard of first sale for circumstances that characterize many university inventions. When the probability of technical success is small but increasing with the investment made in development, as would be the case for inventions that are disclosed and licensed as merely a proof of concept, we would expect a u-shaped hazard of termination and an inverse u-shaped hazard of first sale. Indeed, the competing risks regression models we examine for MIT inventions reveal this pattern. We also find support for the view that appropriability of returns is negatively related to the hazard of termination.

These results contribute, not only to the growing literature on innovation based on university research, but also to the broader literature on patent strength 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 relation between patent length and the rate of innovation, and Lerner (2002) finds empirical support for such a relation. 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.[16] Our results differ in that we explicitly incorporate the uncertainty associated with development of university inventions and we abstract from strategic issues. Both our theory and empirical analysis presume that firms licensing these inventions intend to commercialize them. We believe that this is a fair assumption. March-in rights contained in the Bayh-Dole Act provide strong incentives for technology transfer offices to find licensees they believe will commercialize the inventions. In their survey of US universities, Thursby et al (2001) found that all offices[17] claimed to include milestones and other incentive mechanisms to prevent shelving, and Dechenaux et al. (2002) examine the role of milestones and consulting in facilitating commercialization. Nonetheless, if shelving were to occur, it would most likely be done by continuing the license, as dropping the license would return the invention to MIT for possible licensing to a different company. If it is a profitable strategy to delay introduction of an invention to market, the firm may be able to accomplish this at minimal cost by paying the small ongoing royalty fees to keep a license going, thereby keeping the invention from going to competitors, but not put much effort into marketing the product. We cannot eliminate this possibility nor identify when it might be happening.

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.[18] 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)).[19]

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

[17]There are examples of the use of milestones to terminate MIT licenses. 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.

[18]Katherine 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.

[19]Under the invent-around scenario the university may still receive rents if the license involved

References

[1] Adams, J. (1990) "Fundamental Stocks of Knowledge and Productivity Growth," *Journal of Political Economy*, Vol. 98, pp.673-702.

[2] Agrawal, A. and R. Henderson (2002) "Putting Patents in Context: Exploring Knowledge Transfer from MIT," *Management Science,* Vol. 48, pp. 44-60.

[3] Cohen, W. M., R. Florida, L. Randazzese and J. Walsh (1998) "Industry and the Academy: Uneasy Partners in the Cause of Technological Advance," in Roger Noll (ed), *Challenges to Research Universities*, Washington, D.C.: The Brookings Institution, pp. 171-199.

[4] Colyvas, J., M. Crow, A. Gelijns, R. Mazzoleni, R.R. Nelson, N. Rosenberg, and B.N. Sampat (2002) "How Do University Inventions Get Into Practice," *Management Science*, Vol. 48, pp. 61-71.

[5] Dechenaux, E., J. Thursby, and M.C. Thursby (2002) "Moral Hazard and University License Contracts: The Role of Milestones, and Consulting."

[6] Gallini, N.T. (2002) "The Economics of Patents: Lessons from Recent U.S. Patent Reform," *Journal of Economic Perspectives*, Vol. 16, pp. 131-154.

[7] Goel, R.K. (1996). "Uncertainty, Patent Length and Firm R&D," *Australian Economic Papers*, 35, pp. 74-80.

[8] Goldfarb, B. (2002) *Three Essays in Technological Change*, Ph. D. Dissertation, Stanford, Stanford University.

[9] Grossman, G. and C. Shapiro (1986) "Optimal Dynamic R&D Programs," *RAND Journal of Economics,* Vol. 17, pp. 581-593.

[10] Han, A. and J. Hausman (1990) "Flexible Parametric Estimation of Duration and Competing Risk Models," *Journal of Applied Econometrics*, 5 (1), 1-28.

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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.

[11] Henrekson, M. and B. Goldfarb (2002) "Bottom-Up vs. Top-Down Policies towards the Commercialization of University Intellectual Property," *Research Policy*, forthcoming.

[12] Horowitz, A.W. and E.L.-C. Lai (1996) "Patent Length and the Rate of Innovation," *International Economic Review*, Vol. 37, pp. 785-801.

[13] Jaffe, A. (1989) "Real Effects of Academic Research," *American Economic Review,* Vol. 79, pp. 957-70.

[14] Jensen, R. (2002) "Innovative Leadership: First-mover Advantages in New Product Adoption," *Economic Theory,* forthcoming.

[15] Jensen, R. and M.C. Thursby (2001) "Proofs and Prototypes for Sale: The Licensing of University Inventions," *American Economic Review*, Vol. 91, pp. 240-259.

[16] Kalbfleisch, J.D. and R.L. Prentice (1980) *The Statistical Analysis of Failure Time Data.* Wiley Series in Probability and Statistics.

[17] Kamien, M. and N. Schwartz (1971) "Expenditure Patterns for Risky R&D Projects," *Journal of Applied Probability*, Vol. 8, pp.60-73.

[18] ______________________________ (1974) "Patent Life and R&D Rivalry," *American Economic Review,* Vol. 64, pp. 183-187.

[19] Lancaster, T. (1990) *The Econometric Analysis of Transistion Data*, Cambridge, Cambridge University Press.

[20] Lerner, J. (1994) "The Importance of Patent Scope: An Empirical Analysis,"*RAND Journal of Economics*, Vol. 25, pp. 319-333.

[21] Lerner, Joshua (2002) "150 Years of Patent Protection," *American Economic Review: Papers and Proceedings*, Vol. 92, pp. 221-225.

[22] Levin, R., W. Chen, and D. Mowery (1985) "R&D appropriability, opportunity, and market structure: New evidence on some Schumpeterian hypotheses," *American Economic Association Papers and Proceedings*, Vol. 75, pp. 20-24.

[23] Levin, R., A. Klevorick, R. Nelson, and S. Winter (1987) "Appropriating the returns from industrial research and development," *Brookings Papers on Economic Activity*, Vol. 3, pp. 783-820.

[24] Mansfield, E. (1995) "Academic Research Underlying Industrial Innovations: Sources, Characteristics, and Financing," *The Review of Economics and Statistics*, Vol. 77, pp. 55-65.

[25] McCall, B. (1996) "Unemployment Insurance Rules, Joblessness, and Part-Time Work," *Econometrica* Vol. 64 , pp. 47-682.

[26] Nelson, R. (2001) "Observations on the Post-Bayh-Dole Rise of Patenting at American Universities," *Journal of Technology Transfer* Vol. 26, pp. 13-19.

[27] Roberts, K. and M.L. Weitzman (1981) "Funding Criteria for Research, Development, and Exploration Projects," *Econometrica*, Vol. 49, pp. 1261-1288.

[28] Rosenkopf, L. and A. Nerkar (2001) "Beyond local search: Boundary Spanning, Exploration, and impact in the optical disc industry," *Strategic Management Journal*, 22(4), pp. 287-306.

[29] Ross, S. (1983) *Introduction to Stochastic Dynamic Programming,* Academic Press.

[30] Shane, S. (2000) "Prior Knowledge and the Discovery of Entrepreneurial Opportunities," *Organization Science*, Vol. 11, pp. 448-469.

[31] Shane, S. (2001) "Technological opportunities and new firm creation," *Management Science*, Vol. 47, pp. 205-220.

[32] Thursby, J, R. Jensen, and M.C. Thursby (2001) "Objectives, Characteristics and Outcomes of University Licensing: A Survey of Major U.S. Universities," *Journal of Technology Transfer*, Vol. 26, pp. 59-72.

[33] Thursby, J., and M.C. Thursby (2002) "Who is selling the ivory tower? Sources of growth in university licensing," *Management Science*, Vol. 48, pp. 90-104.

[34] Zucker, L., M. Darby and M. Brewer (1998) “Intellectual Capital and the Birth of U.S. Biotechnology Enterprises,” *American Economic Review*, Vol. 88, pp. 290-306.

Table 1:

Descriptive statistics of MIT invention commercialization efforts – exclusive patents (unweighted)

Variable	Mean	SD	Minimum	Maximum
FIRST SALE	0.21	0.41	0	1
TERMINATION	0.33	0.47	0	1
START-UP	0.33	0.47	0	1
PATENT SCOPE	1.34	0.64	1	6
CITATIONS TO PRIOR ART	9.97	11.93	0	70
INDUSTRY FUNDED	0.17	0.37	0	1
PATENT AGE (at first observation of attempt)	4.14	3.39	0	16
PATENT AGE (at last observation of attempt)	6.71	4.16	0	20
RADICAL	5.81	5.41	0	57
APPROPRIABILITY	5.99	0.42	4	6.53
DRUG PATENT	0.22	0.41	0	1
CHEMICAL PATENT	0.31	0.46	0	1
ELECTRONIC PATENT	0.26	0.44	0	1
OTHER PATENT	0.21	0.41	0	1

Total: 803 licensed patents

Table 2:

Survival Rates Exclusively Licensed Patents

Period	Terminated	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	0	0	2	13	15
13	0	0	7	6	13
14	0	0	2	4	6
15	0	0	2	2	4
16	0	0	2	0	2
Total	269	168	366		2875

Table 3: Competing Risks Regressions - exclusive licenses

Dependent Variables: First sale, Termination

	(i)		(ii)		(iii)		(iv)		(v)	
	First Sale	**Termination**	**First Sale**	**Termination**	**First Sale**	**Termination**	**First Sale**	**Termination**	**First Sale**	**Termination**
AGE	0.26	-0.16	0.26	-0.16	0.29	-0.17	-0.133	-0.311	-0.151	-0.314
	(2.52)	*(-1.95)*	*(2.53)*	*(-1.93)*	*(2.75)*	*(-2.07)*	*(-2.04)*	*(-4.51)*	*(-2.51)*	*(-4.80)*
AGE^2	-0.009	0.008	-0.009	0.01	-0.11	0.008	0.011	0.016	0.012	0.017
	(-1.59)	*(1.55)*	*(-1.58)*	*(1.69)*	*(-1.76)*	*(1.59)*	*(2.80)*	*(3.94)*	*(3.19)*	*(4.19)*
PATENT SCOPE	0.336	-0.135	0.33	-0.098	0.36	-0.135	-0.035	-0.31		
	(2.91)	*(-1.07)*	*(2.93)*	*(-0.80)*	*(3.19)*	*(-1.09)*	*(-0.31)*	*(-2.6)*		
PRIOR ART CITED	-0.008	0.018	-0.01	0.016	-0.019	0.02	-0.033	0.015		
	(-0.42)	*(1.85)*	*(-0.45)*	*(1.61)*	*(-0.99)*	*(2.24)*	*(-1.68)*	*(1.72)*		
RADICALNESS	0.013	0.021	0.14	0.024	0.029	0.017	0.019	0.018		
	(0.46)	*(0.91)*	*(0.49)*	*(1.04)*	*(1.03)*	*(0.77)*	*(0.68)*	*(0.85)*		
INDUSTRY FUNDED	0.308	-0.577	0.304	-0.59	0.245	-0.54	0.32	-0.45		
	(1.28)	*(-2.35)*	*(1.27)*	*(-2.42)*	*(1.04)*	*(-2.23)*	*(1.40)*	*(-1.91)*		
APPROPRIABILITY	-0.651	-0.402	-0.649	-0.36	-0.652	-0.402				
	(-5.47)	*(-3.48)*	*(-5.47)*	*(-3.26)*	*(-6.13)*	*(-3.88)*				
START-UP	0.04	0.414			0.032	0.434				
	(0.20)	*(2.68)*			*(0.16)*	*(2.82)*				
DRUG PATENT	0.184	-0.09	0.179	-0.16						
	(0.53)	*(-0.34)*	*(0.51)*	*(-0.63)*						
CHEMICAL PATENT	0.489	-0.18	0.485	-0.23						
	(1.68)	*(-0.79)*	*(1.67)*	*(-1.01)*						
ELECTRONIC PATENT	-0.374	-0.14	-0.377	0.11						
	(-1.00)	*(0.58)*	*(-1.01)*	*(0.46)*						
Chi-squared tests:										
Age and Age^2 jointly 0	14.69**	4.94*	15.89**	4.02**	18.18**	6.04**	10.57**	21.40**	11.80**	23.99**
Drugs, Chem, Elec jointly 0	8.66**	2.63	8.65**	3.31**						
All jointly zero	61.49**		61.42**		52.18**		15.71**		11.80*	
Nb observations	2875		2875		2875		2875		2875	
Log likelihood	-1342.94		-1346.45		-1348.87		-1392.69		-1406.42	

* significant at the 90% level; ** significant at the 95% level
(t-statistics in parentheses below estimates)

<u>Figure 1:</u>

Conditional failure probabilities for exclusively licensed patents

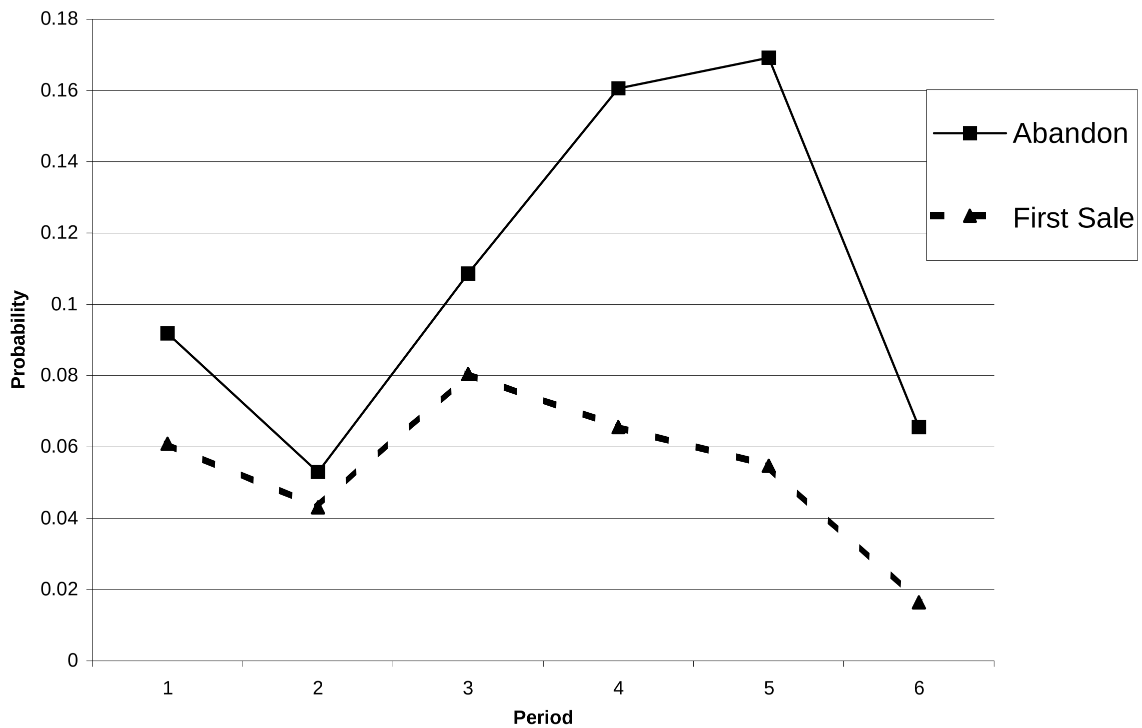


Figure 2:

Empirical survival functions by technological type for exclusively licensed patents

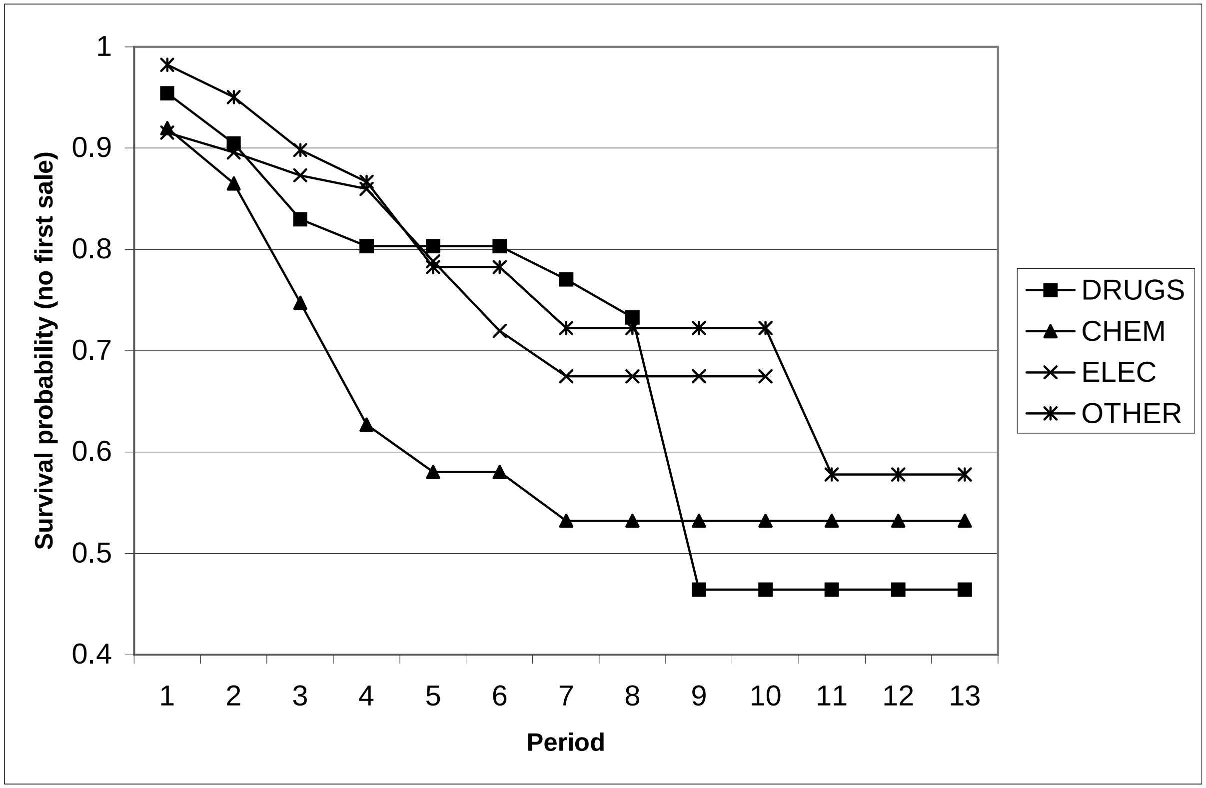
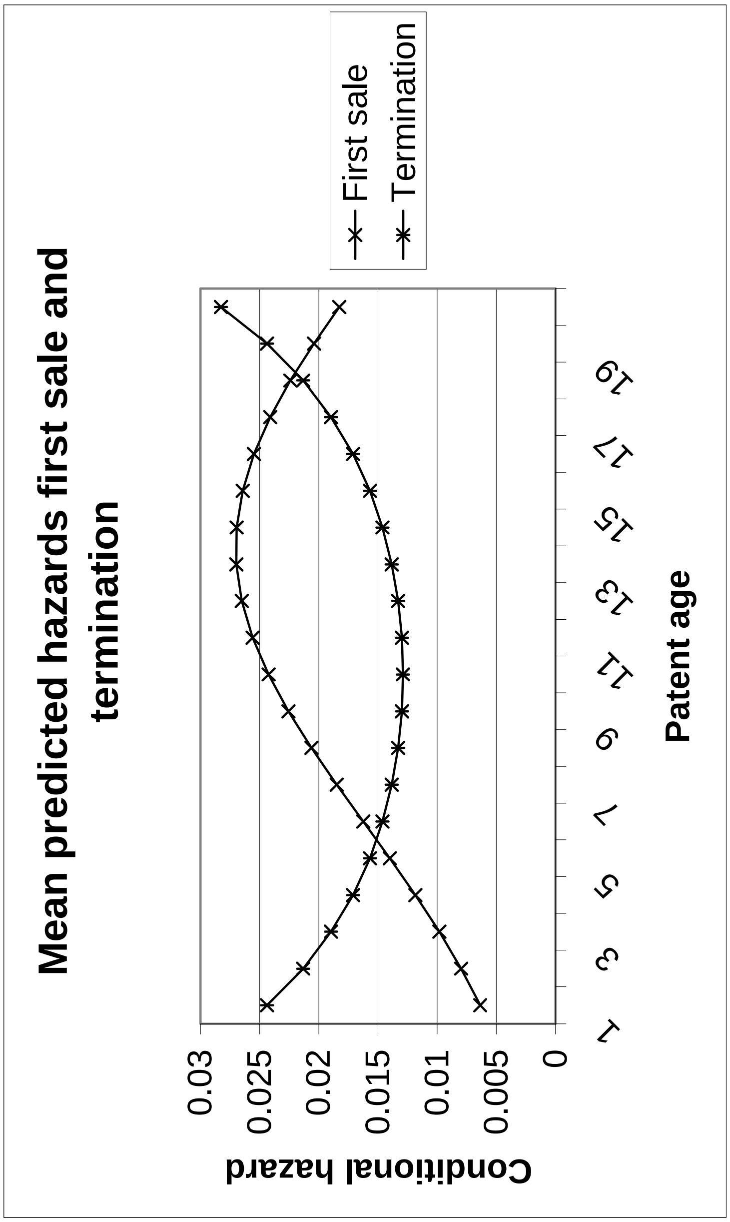


Figure 3


Mean predicted hazards first sale and termination
Conditional hazard
0.03
0.025
0.02
0.015
0.01
0.005
0
1
3
5
7
9
11
13
15
17
19
Patent age
First sale
Termination