Licensing in the Patent Thicket - Timing and Benefits

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Abstract

Licensing can be a solution for hold-up in patent thickets. In this paper we study whether licensing is an effective solution for hold-up. To do this we distinguish between ex ante and ex post licensing. A theoretical model shows that firms' expectations of blocking in a patent thicket determine whether they license ex ante while ex post licensing arises if expected blocking was low but realized blocking turns out to be high. It can also be shown that ex ante licensing will allow firms to reduce their patenting efforts. A sample selection model of licensing is derived from the theoretical model. Applying this to data from the semiconductor industry we show that licensing does help firms to resolve blocking. However, the probability of observing licensing decreases as fragmentation of property rights increases and arises mainly between large firms with similar market shares. Licensing experience is also an important determinant of licensing. As expected ex ante licensing allows firms to reduce the level of patenting.

JEL: L13, L49, L63.

Keywords: Hold-Up Problem, Licensing, Innovation, Patent Race, Patent Thicket.

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1 Introduction

Explosive growth of patenting world wide has raised fears that patent systems may inhibit economic activity rather than foster it (Jaffe and Lerner, 2004; Bessen and Meurer, 2008). The growth in patenting arising from legal reform (Jaffe, 2000), increasing technological complexity (von Graevenitz et al., 2008) and feedback mechanisms within the patent system (Ziedonis, 2004) is leading to patent thickets (Heller and Eisenberg, 1998; Shapiro, 2001). These occur in semiconductor- and information technology (Hall and Ziedonis, 2001; Ziedonis, 2004) and increasingly in other fields such as genetic diagnostic testing (Huys et al., 2009).

In a patent thicket many firms hold patents protecting components of a single technology. Whenever a firm uses such a technology it is vulnerable to hold-up by firms holding blocking patents (Grindley and Teece, 1997; Shapiro, 2001). The threat posed by blocking patents frequently induces firms to build large patent portfolios in costly patent portfolio races. These bolster firms' bargaining positions in disputes with rivals (Grindley and Teece, 1997; Lemley, 2001). Patent thickets undermine the proper functioning of patent systems: they raise costs of using complex technology and increase incentives to acquire marginal patents.

Due to these aggregate trends patenting strategy (Harhoff and Wagner, 2009), licensing (Grindley and Teece, 1997; Clark and Konrad, 2008) and patent litigation (Somaya, 2003) have become increasingly significant problems for firms operating in complex technology industries. The aggressive litigation and licensing strategy pursued by Texas Instruments first brought this home to their rivals more than twenty years ago (Grindley and Teece, 1997) and the point has recently been underlined by the court case surrounding RIM's push email service.

This paper provides an empirical study of licensing in order to identify benefits and costs of firms' licensing strategies in complex technologies. To do this we distinguish between two licensing strategies: licensing ex ante or ex post. Ex ante licensing contracts commit firms to provide future patents on a technology to other firms. Such contracts allow firms to guarantee each other "freedom to operate" (Grindley and Teece, 1997) before R&D investments are made and may significantly reduce costs of R&D in the context of a patent thicket. Ex post licensing contracts are preceded by a "patent portfolio race" [1] in which firms race to acquire patents on a technology. After the race, firms may have to grant each other rights to patents on existing technologies.[2]

While both strategies may in principle allow firms to reduce costs of patenting in patent

[1]This phrase is coined by Hall and Ziedonis (2001).

[2] Examples and further descriptions of ex ante and ex post licenses may be found in Appendix D.

thickets it is not clear that they do in practice. Ex ante licensing requires considerable ability to plan ahead. Also its usefulness may be limited where patent rights become highly fragmented so that a single cross-licensing contract has limited effects. Ex post licensing requires less foresight but may impose costly delays on firms. Its usefulness may also be reduced by increased fragmentation. Both types of licensing may require specific legal and organizational expertise. Therefore, we investigate how licensing is actually employed to resolve hold-up, using data on licensing contracts between semiconductor firms.

We draw on a data set of licensing contracts announced between 1989 and 1999 in the semiconductor industry and document the main trends in licensing for this industry. Our data show that most contracts are signed ex ante and that it is mainly the variation in ex ante licensing over the sample period which explains variation in the aggregate level of licensing in this industry. Correlating the levels of licensing with different aggregate and firm specific variables we find that the level of blocking patents is likely to explain licensing trends better than variables such as firm numbers or patent applications.

Firms anticipating a patent portfolio race face a three way choice between licensing ex ante or ex post or not licensing at all. Building on a theoretical model we show that firms first choose between ex ante licensing or delaying their decision. If the decision is delayed ex post licensing arises only where blocking becomes sufficiently severe. We show that this sequence of decisions can be modeled using a selection model. Selection models are increasingly being adopted to study the outcomes of strategic decisions in the management literature (Masten, 1993; Shaver, 1998; Villalonga and Amit, 2006). We study both the licensing strategy chosen and its effect on firms' patenting levels using sample selection models.

Our results confirm that firms' expectations of blocking and later realizations of blocking determine licensing outcomes. Moreover, a switching regression shows that ex ante licensing significantly lowers firms' patenting levels, confirming that ex ante licensing can have important benefits. However, increased fragmentation of patent ownership (Ziedonis, 2004) reduces the likelihood of licensing: growing patent thickets undermine one option firms have to reduce the problem of hold-up. Additionally, we find that licensing is mostly undertaken by firms with large market shares, confirming results of Galasso (2007). Finally, our results indicate that the capability to engage in licensing is acquired cumulatively.

The test of our theoretical predictions rests crucially on our ability to identify blocking. Since we must rely on firm level data to measure blocking we provide a robustness check for this approach using data from European patents. This European data contains a direct measure of blocking and allowing us to test and provide support for our results.

The remainder of the paper is organised as follows: in Section 2 we describe licensing trends in the semiconductor industry. In Section 3 we discuss our theoretical model. In Section 4 we derive an empirical implementation of the model. Then in Section 5 we discuss the data and Section 6 contains our empirical results. Finally, Section 7 concludes.

2 Licensing in the Semiconductor Industry

In this section we describe firms' licensing behavior in the semiconductor industry. In a large sample study of licensing Anand and Khanna (2000) find that the level of licensing in the semiconductor industry is high, relative to other industries. This industry, therefore, provides a natural context in which to study the effects of licensing in a patent thicket. Furthermore, the effects of licensing on innovative activity in the semiconductor industry are of interest in their own right: Jorgenson (2001) argues that the semiconductor industry is one of the most important high technology industries, since its prices significantly affect many other downstream industries. We show that licensing trends have developed in a surprising way given entry, exit and patenting in the semiconductor industry. Additionally, we investigate whether the blocking strength of firms' patent portfolios or fragmentation of patent portfolios might explain firms' licensing behavior. The former emerges as the most likely determinant of licensing.

To study licensing we have constructed a data set comprised of 847 licensing contracts between 268 firms. It contains information about the date, the partners and the purpose of the license as well as data on firms' revenues, market shares and patents. A detailed description how the data were constructed is provided in Appendix C.[3]

Figure 1a shows that total revenues of all semiconductor firms grew substantially over the period of our sample. Mirroring this there was also a large increase in the number of active semiconductor firms. However, the figure also demonstrates that aggregate revenue almost stopped growing after 1996. This coincided with increased turbulence in the industry, as a much larger proportion of semiconductor firms was affected by entry and exit than before.

The semiconductor industry also experienced a strong surge in patenting activity after 1985

[3]Note that the number of ex ante and ex post licenses goes down to 250 and 294, respectively, in our sample statistics due the fact that we condition on firms having produced in the industry. The number of licensing contracts further decreases to 212 ex ante and 261 ex post licensing contracts in our regressions due to missing values.

Figure 1a

Growth of revenues and firm numbers in the semiconductor industry

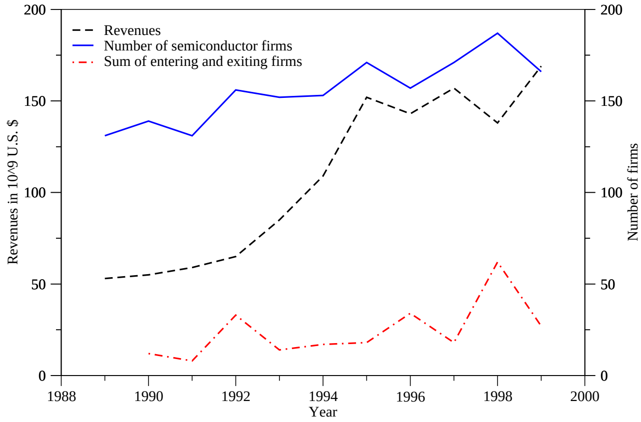
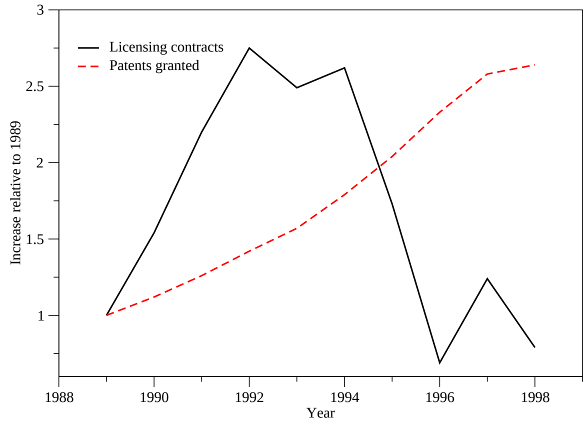


Figure 1b

Licensing and patenting activity in the semiconductor industry



(Hall and Ziedonis, 2001; Ziedonis, 2003, 2004). Figure 1b shows the level of granted patents and licensing contracts relative to 1989. The number of new patents granted to semiconductor firms more than doubled over the period of our sample. This development is carefully investigated by Hall and Ziedonis (2001) who argue that it is due to strategic patenting in the face of an emerging patent thicket. Surprisingly, the increase in patenting by semiconductor firms does not lead to a proportionate increase of licensing amongst these firms. Figure 1b shows that the number of new licensing contracts amongst semiconductor firms in our sample shows no obvious relation to the increase in granted patents. This is surprising because we might expect there to be a greater need for licensing as the number of patents grows.[4]

Figure 2a below shows the average number of licensing contracts per firm in the semiconductor industry. The figure displays a hump shape just as the absolute number of licensing contracts does. This rules out an explanation of the number of licenses based on the number of semiconductor firms. Between 1991 and 1994 there were almost as many licensing contracts as firms. The decline in licensing activity after 1994 also remains clearly visible.[5]

Next, we introduce the distinction between ex ante and ex post licensing. As mentioned above, ex ante licensing contracts are those contracts which show a commitment to provide a certain technology to other firms before the technology has been explored. Ex post contracts cover those cases in which firms grant rights to other firms for already existing technologies.

[4]Information on the duration of a subset of licensing contracts in our data suggests that these contracts last for roughly 5 years. We used this estimate and similar ones to simulate the stock of licensing contracts based on our data. This shows that the reduction in licensing contracts after 1994 is so large that also the stock of contracts diminishes after that date. Therefore, the changes we observe in new licensing contracts are not the result of a saturation of the demand for licensing contracts.

[5]Vonortas (2003) investigates a much larger sample of licensing contracts drawn from the same database (Thomson Financial) as ours. He shows that the decline in licensing activity we observe between 1994 and 1996 occurs across a wide set of manufacturing industries. Thomson Financial confirmed to us that the observed patterns are not due to changes in data collection methods.

Figure 2a
The frequency of licensing per firm in the semiconductor industry

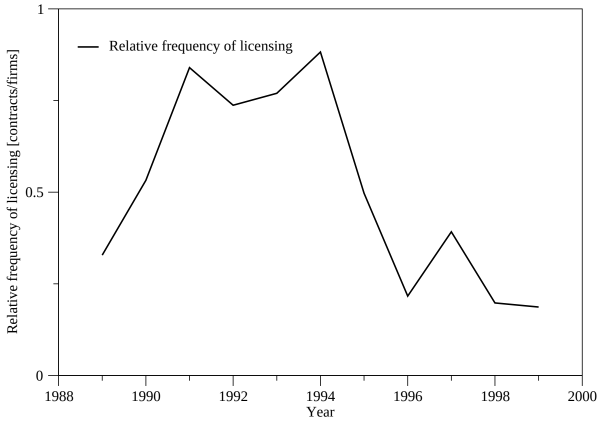
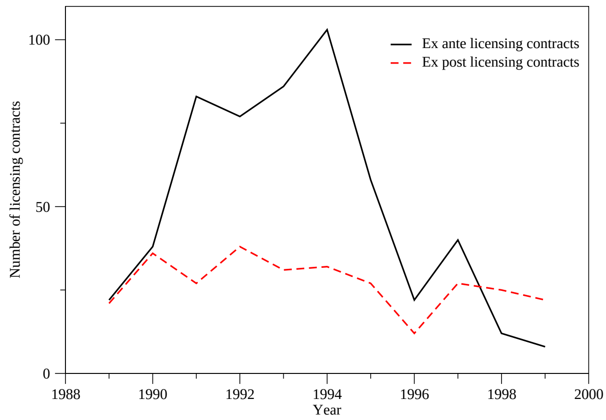


Figure 2b
Total ex ante and ex post licensing contracts in the semiconductor industry



According to the information in the synopsis of the licensing contracts, we categorized the licensing contracts into ex ante and ex post licensing contracts, see also Appendix B for more detailed information on this procedure.

Figure 2b shows that ex ante licensing is far more variable over the period of our sample than ex post licensing. As noted in the introduction this finding is surprising in light of the previous literature on patent thickets. This literature has not noted the importance of ex ante licensing as a means of preventing hold-up (Grindley and Teece, 1997; Shapiro, 2001). In sum, Figures 2a and 2b show clearly that, over the period of our sample, the increase in overall licensing is predominantly a result of a strong increase in ex ante licensing.

To gain a better understanding of what underlies the patterns of ex ante and ex post licensing illustrated in Figures 2a and 2b we present information on the top 20 innovating firms in the semiconductor industry in Table 1. The table provides information on the number of patents granted to each firm, their cumulative revenues and their average market shares between 1989 and 1999. Furthermore, we report the percentage of licensing contracts of both types, each firm was a party to. In each column the top three firms are highlighted in boldface.

Table 1 shows that Texas Instruments and Intel account for over one fifth of all ex post licensing agreements.[6]Previous studies [Grindley and Teece (1997); Shapiro (2001, 2003)] tended to focus on these firms which may explain why they devote less attention to ex ante licensing. The number of ex ante licensing agreements is spread evenly across firms represented here. In spite of the difference between ex ante and ex post licensing it is clear that nearly all firms engage in both types of licensing to a significant degree. Twenty nine percent of contracts in our sample are signed by firms with experience of both ex ante and ex post

[6]No agreements between the two firms are recorded in our data.

licensing.

Table 1: Licensing by the Top Semiconductor Innovators 1989-1999

Company	Patents	Cumulative revenues*	Average market shares (%)	Percent of total licensing	Percent of ex ante licensing	Percent of ex post licensing
IBM	**3,802**	21,909	1.85	**5.55**	**6.92**	3.02
NEC	**3,072**	**81,677**	**6.91**	3.66	4.19	2.68
TOSHIBA	**3,041**	**69,974**	**5.92**	4.84	**5.46**	3.69
SONY	2,343	17,690	1.50	2.01	2.00	2.01
FUJITSU	1,894	40,520	3.43	3.42	3.28	3.69
TEXAS INST.	1,837	56,006	4.74	**8.74**	**5.46**	**14.77**
MICRON TECH.	1,746	15,836	1.34	1.06	0.73	1.68
MOTOROLA	1,739	66,700	5.65	5.31	**6.56**	3.02
SAMSUNG	1,645	46,344	3.92	2.95	2.55	3.69
MATSUSHITA	1,367	28,021	2.37	2.24	2.19	2.35
AMD	1,085	20,725	1.75	2.48	1.64	4.03
S.G.S. THOMSON	994	17,991	1.52	1.89	2.19	2.34
INTEL	938	**135,069**	**11.43**	**5.67**	4.74	**7.38**
UNITED MICRO.	776	3,108	0.26	0.24	0	0.67
NAT. SEMI. CORP.	639	22,571	1.91	3.90	3.46	**4.70**
HYUNDAI EL.	590	18,450	1.56	0.83	0.36	1.68
LG CABLE & MACH.	546	8,445	0.71	0.47	0.73	0
LSI LOGIC CORP.	453	11,335	0.96	2.60	1.82	4.03
AT & T	431	5,531	0.47	2.36	2,55	2,01
OKI ELECTRIC IND.	370	12,872	1.09	1.89	1.82	2.01
Total number (industry)	96,590	1,181,420	100%	847	549	298

*Revenues are stated in millions of 1989 dollars.

Table 2 provides a comparison of all firms that undertook ex ante and ex post licensing. This comparison does not reveal differences between firms engaged in ex ante and ex post licensing contracts. In part this finding is due to the fact that some firms use both types of licensing contract. In particular, Table 2 shows that the average firm engaged in approximately 6 contracts between 1989 and 1999. The average firm engaging in ex ante (ex post) licensing was granted 128 (137) patents and its patent stock attracted a total of 1,056 (1,145) citations over the sample period. All distributions of these variables are highly skewed.

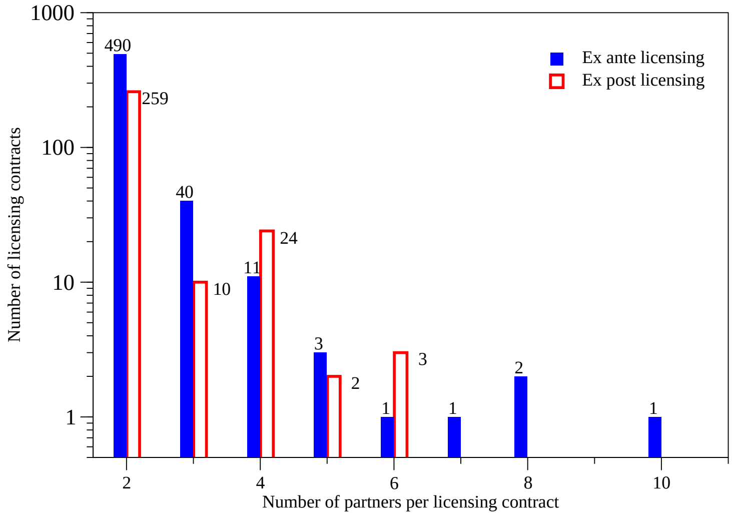
Table 2: Sample Statistics for Firms by Licensing Contract Type

	Ex post licensing				Ex ante licensing			
Variable	Mean	Std. dev.	Min.	Max.	Mean	Std. dev.	Min.	Max.
Number of parties	2.47	0.98	2	6	2.39	1.16	2	10
Total contracts	6.35	11.02	1	44	5.57	7.25	1	38
Market shares (%)	2.9	3.3	0	16.4	2.9	2.9	0	16.4
Patent grants	128	198	0	873	137	192	0	873
Forward citations	1,056	1,341	0	6,282	1,145	1,413	0	6,282

To pursue the comparison of ex ante and ex post licensing we also investigate the number of firms involved in each licensing contract. The average number of firms involved in a contract is between two and three. The histogram in Figure 3 illustrates that the vast majority of contracts in this sample is bilateral.

Figure 3

Distribution of participant numbers in ex ante and ex post licensing contracts



Overall, these comparisons of firms engaged in ex ante and ex post licensing suggest that the observed trends are not the result of greater licensing activity by a group of firms specializing in ex ante licensing. We must rather account for all firms in the industry when analyzing the decision whether to engage in ex ante and ex post licensing. Furthermore, an aggregate measure of the strength of the patent thicket, in form of patent counts, does not explain the development of licensing between semiconductor firms in aggregate. Neither is this measure related to the choice between ex ante and ex post licensing. In order to explain firms' choices between ex ante and ex post licensing contracts, we turn to measures of the patent thicket at the level of firm pairs. Hence, we move from a focus on individual firms to a focus on firm pairs.

Figure 4a presents a measure of blocking between firms in a pair. We construct all possible firm pairs between firms with positive market shares in the semiconductor industry. For these pairs we measure blocking by interacting a measure of technological proximity with a measure of cross citations within the pair.[7] If firms patent in similar technology classes with the same intensity and cite each other frequently the measure is high. Figure 4a reveals that blocking initially increased and then decreased over the sample period. The decrease is mainly the result of the larger number of semiconductor firms which causes the number of potential firm pairs to rise significantly. Many of the pairs formed with new entrants into the industry exhibit low levels of blocking, as we would expect. Overall, Figure 4a indicates that blocking may provide a large part of the explanation for the licensing trends discussed previously.

Figure 4a

Blocking in firm pairs

Figure 4b

Fragmentation in pairs

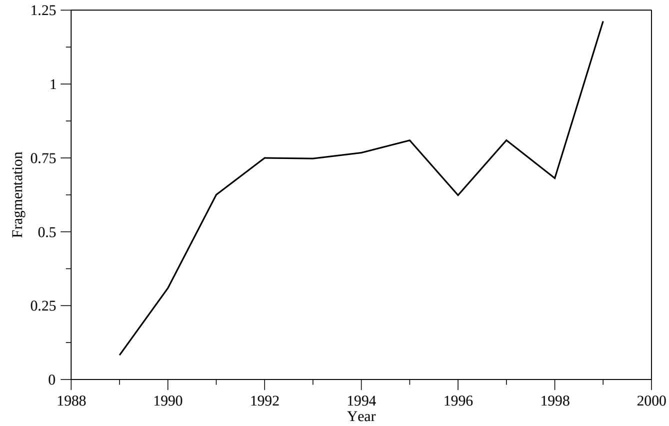


Figure 4b presents the evolution of fragmentation of technology ownership over time based on the citations from the patents held by a firm pair.[8] Ziedonis (2004) shows that fragmentation explains some of the large increase in patenting levels in the semiconductor industry. She argues that the fragmentation index represents a measure of hold-up potential. If licensing

[7] For a precise definition of this measure refer to Section 5 below.

[8] See Section 5 for further information on the variable definition.

contracts resolve such potential we might expect licensing to be correlated with fragmentation. Figure 4b does not reveal an obvious relationship however.

Next, we provide a theoretical model to clarify how blocking affects R&D incentives and licensing behavior. The model is tested in the following sections.

3 Licensing and Patenting in the Patent Thicket

In Appendix B we introduce a theoretical model of patenting and licensing behavior of firms using complex technologies. In this section we discuss the set up of the model, its main predictions and the intuition for them. The model shows how firms' expectations of the level of blocking patents affect their R&D investments and licensing choices.[9] We adapt existing patent race models to capture the main forces at work in patent portfolio races.

In a conventional patent race model firms race for one patent. In contrast, patent portfolio races in complex technologies are races for the largest patent portfolio in the technology. In disputes over patent validity or negotiations over cross licensing agreements the size of patent portfolios directly determines firms' bargaining positions (Grindley and Teece, 1997; Lemley, 2001; Hall and Ziedonis, 2001; Ziedonis, 2004). We make two assumptions to capture the main R&D investment incentives at work in a patent portfolio race. First, we assume firms invest in R&D to explore a technology and are able to patent parts of the technology at a constant rate once they have achieved this knowledge. Secondly, we assume that some patent rights are likely to overlap as soon as firms patent the technology simultaneously. Patents that overlap are susceptible to be challenged in court, which may lead to hold-up. Patent overlap is due to the widely documented difficulties of patent offices to clearly delineate claims of different patents (Lemley, 2001; Federal Trade Commission, 2003).

Given these two assumptions, we show that a race to begin patenting a technology first, yields the following outcomes: the winner of the patent portfolio race will have a larger patent portfolio and will posses more patents that are not threatened by hold-up. Both winner and loser of a patent portfolio race will hold some patents that may be held up and will therefore seek to cross license patents. Anticipating this outcome, firms may seek to license ex ante, if firms expect that a large proportion of patents will be blocked. Where firms do not perceive the likelihood of blocking to be high, they will postpone the decision to license ex post.

[9] The model is developed as far as is necessary to derive these predictions. A more extensive development is beyond the scope of this paper and is left for future work.

It is instructive to compare our model to Fershtman and Kamien (1992) who model patent races for two patents. Their model is directed at discrete technologies with complementarity between patents. Our analysis is directed at highly complex technologies in which firms acquire very large patent portfolios. There are two main differences between the models. First, they model a situation in which firms compete for two perfectly complementary patents. Among other questions, they study how ex post licensing affects R&D incentives. In contrast, in our analysis patent portfolios may be partial complements. This means that production may be only partly blocked by patents of the rival firm. We study how variation in blocking affects R&D and licensing incentives. Secondly, in their analysis firms may cross license only ex-post, as soon as one of the two firms obtains a patent. As there are exactly two patents, a separate race for the second patent may ensue and firms are able to adjust their R&D efforts before this time. In contrast, in our analysis firms determine R&D investments ex ante. Firms engaged in patent portfolio races do not exactly know how many patents rival firms have applied for and how these may overlap with their own. Therefore, firms are unable to adjust their R&D efforts in response to rivals' patenting. Here, uncertainty is due to the lag with which patent applications turn into granted patents and low investments in patent examination (Lemley, 2001).[10] Therefore, our assumption of fixed ex ante investments which determine the probability of amassing a larger portfolio of patents seems appropriate.

We study two solutions to the problem of blocking: ex ante and ex post licensing. Ex ante licensing contracts prevent hold-up for a specific period. They cover new patents that arrive in that period. Firms that do not license ex ante keep open the option to license ex post or to not license at all. Ex post contracts resolve hold-up given firms' existing patents.

In our model we allow each firm's investment to increase the probability that the firm will be able to start patenting in the next instant. In this way we endogenize the length of time in which only the first firm patents and obtains unblocked patents. We also endogenize the share of blocked patents as a function of the likelihood of blocking. We show that R&D investments are strategic complements in this setting.

The following propositions are derived from the model:

Proposition 1

Firms license ex ante, if the likelihood of blocking is expected to be high.

The expected value of delaying the licensing decision corresponds to the value of the

[10]Hall et al. (2005) show that in the early 1990's patents took on average of 1.76 years to grant. Therefore, even firms watching patents granted to rivals would have learned about their research with substantial delay.

choice between licensing ex post (V_p) and not licensing at all (V_n). The value of both of these alternatives decreases in the likelihood of blocking. If there is no licensing, then the share of patents that cannot be used increases in the likelihood of blocking. This decreases the value of not licensing. Now consider the expected value of ex post licensing. In Appendix B we show that firms seek to reduce the possible cost from losing the patent portfolio race by decreasing the length of the period in which the winner obtains unblocked patents. Therefore, a high likelihood of blocking leads to greater R&D investments. We show that this reduces the expected value of ex post licensing. The value of ex ante licensing (V_a) is not affected by the likelihood of blocking. Therefore, if the likelihood of blocking becomes sufficiently high, firms will license ex ante.

Proposition 2

Firms license ex post if the licensing decision was delayed and realized blocking is high.

If firms' expectations that the likelihood of blocking is low are revealed to be false, then firms will resolve the problem of blocked patents by licensing patents ex post. This allows the firms to avoid costly litigation.

Proposition 3

The level of R&D investments and patenting is lowest if the likelihood of blocking is low.

A higher likelihood of blocking raises R&D investments under ex post licensing. We show that R&D investments under ex ante licensing correspond to those under ex post licensing when there is no blocking. Thus, there will be more patenting as the likelihood of blocking increases while expected profits drop.

The model we have summarized here contains the exogenous likelihood of blocking but endogenizes the realized level of blocking as a function of firms' R&D investments. This implies that even under ex ante licensing firms will have patent portfolios of different sizes. High expected levels of blocking induce ex ante licensing which leads to lower realized levels of blocking. As a result we find that R&D investment under ex post licensing exceeds investment under ex ante licensing. We test this prediction below.

4 Derivation of an Empirical Model

In this section we provide an empirical model with which to test predictions about effects of blocking on licensing and R&D investment.

4.1 The Choice Between Ex ante and Ex post Licensing

Our theoretical model contains three decisions: the decision to license ex ante, the decision about R&D investments and the decision to license ex post. In the previous section we show that expected blocking determines the values of license ex ante and ex post as well as firms' R&D investments. Figure 2 below presents the sequence of decisions by which firms may self select into the ex post licensing decision. Two decisions may be taken: the ex ante licensing decision and the ex post licensing decision. In the ex ante licensing decision firms' expectations of blocking by another firm determine whether a license with that firm is signed. If firms do not license ex ante the realization of blocking may force them to license ex post. When the realization of blocking is very low costs of licensing do not outweigh its benefits and firms do not license at all.

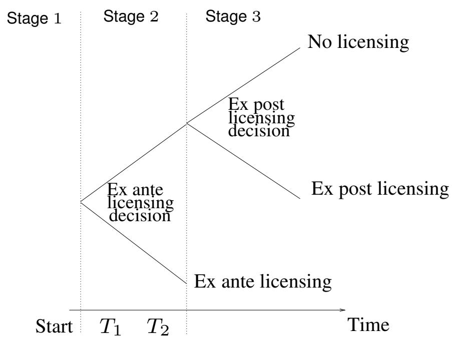


Figure 1: Sequence of decisions in our model

The Ex ante Licensing Decision

Firms license ex ante if this is expected to be more valuable than not licensing ex ante. The value of not licensing ex ante is a function of the likelihood of blocking and of transaction costs of licensing. The selection equation of our empirical model is:

$$\begin{aligned}
\text{prob}(\Pi_a = 1) &= \text{prob}(V_a - T_a - \max(V_p(\beta) - T_p, V_n) + \epsilon > 0) \qquad (1)\\
&= \text{prob}(V_a - T_a - \max(V_p(\beta) - T_p, V_n) > \epsilon)\\
&= \Phi(V_a - T_a - \max(V_p(\beta) - T_p, V_n(\beta))),
\end{aligned}$$

where T_a, T_p are transaction costs associated with ex ante and ex post licensing. ϵ captures random variation in licensing and is assumed to be normally distributed while β denotes the likelihood of blocking. Note that the expected values of ex post licensing (V_p) and not licensing (V_n) are decreasing functions of the anticipated likelihood of blocking (β). This specification for the selection equation of our model provides a testable restriction, if we assume that transaction costs are decreasing in licensing experience:

Hypothesis 1

The probability of observing ex ante licensing increases in the experience a firm has with ex ante licensing and decreases in the experience a firm has with ex post licensing.

Once transaction costs are taken into account the model predicts that we will observe both ex-ante and ex-post licensing, depending on the level of expected blocking. First, the difference between expected values of ex ante (V_a) and ex post licensing (V_p) is a function of the likelihood of blocking: We show that $V_a = V_p = V_n$ if the likelihood of blocking in the firm pair is zero. Then, firms will not license ex ante as the costs of licensing may be avoided. As the likelihood of blocking increases ex post licensing becomes more valuable than not licensing at all ($V_p - T_p > V_n$). At the same time ex ante licensing becomes increasingly more attractive relative to ex post licensing ($V_a > V_p$). Then there is a level of the likelihood of blocking beyond which the firms will prefer ex ante licensing over delaying the licensing decision. The relationship between the expected value of ex post licensing and the likelihood of blocking is nonlinear, therefore we cannot derive an analytical structural expression for ($V_a - \max(V_p(\beta) - T_p, V_n(\beta))$).

Additionally, it is clear that the expected values of ex ante and ex post licensing may depend on the levels of firms' ex ante profits (π_0), the size of their patent portfolios and the number of product markets firms operate in. For all of these variables the theoretical model does not yield testable sign restrictions. Nonetheless, they are likely determinants of firms' licensing choices and we include them in our model as control variables. The resulting specification for the selection equation of our model is:

$$\Pi_a^* = \beta_a^c + \beta_a^{EB} EB + \boldsymbol{\beta}_a^{PM} \boldsymbol{PM} + \boldsymbol{\beta}_a^{PS} \boldsymbol{PS} + \beta_a^{LA} L_A + \beta_a^{LP} L_P + \epsilon \ , \tag{2}$$

where EB is our measure of the likelihood of blocking in a firm pair, $\boldsymbol{PM}$ is a vector of measures capturing firms' product market size, $\boldsymbol{PS}$ is a vector of measures capturing the size of firms' patent stocks and L_A, L_P count the number of previous ex ante and ex post contracts both firms were involved in. We do not observe transaction costs associated with ex ante and ex post licensing directly; we proxy them using firms' licensing experience as measured by L_A and L_P. ϵ is assumed to have a variance of unity and is normally distributed.

The main restriction derived from the theoretical model follows from Proposition 1:

Hypothesis 2

$\beta_a^{EB} > 0.$

We expect the coefficient on expected blocking to be positive, indicating that greater expected blocking raises the probability of observing ex ante licensing.

The Ex post Licensing Decision

After T_2 the loser also starts to patent and the size of the leader's advantage over the loser is clear. Then the choice whether or not to license ex post depends on whether the value of resolving blocking patents outweighs the costs of licensing ex post.

The model outlined in Appendix B shows that conditional on firms' R&D expenditures the value of ex post licensing to both firms is $v_w + v_l$ where v_w, v_l denote the payoffs to the firms winning and losing the patent portfolio race. Then the probability of observing ex post licensing is:

$$\begin{aligned} \text{prob}(\Pi_p = 1) &= \text{prob}(v_w + v_l - V_n - T_p + \eta > 0) \\ &= \text{prob}(v_w + v_l - V_n - T_p > \eta) \\ &= \Phi(v_w + v_l - V_n - T_p), \end{aligned} \tag{3}$$

where η is distributed normally with a variance of unity. The term captures random components of the expected value of not licensing and licensing ex post. This specification yields an additional testable restriction:

Hypothesis 3

The probability of observing ex post licensing is increasing in firms' experience with ex post licensing.

By definition the difference $v_w + v_l - V_n$ is zero if there is no blocking and it is increasing in the realization of blocking. Additionally, we expect that the size of firms' patent portfolios and product market variables will determine how important ex post licensing is. Our model of firms' profit functions is too general to provide clear restrictions on the parameters of these variables. The resulting specification of our model is:

$$\Pi_p^* = v_w + v_l - V_n - T_p + \eta_\triangle = \beta_p^c + \beta_p^B B + \boldsymbol{\beta}_p^{PM} \boldsymbol{PM} + \boldsymbol{\beta}_p^{PS} \boldsymbol{PS} + \beta_p^{LP} L_P + \eta \ , \tag{4}$$

where B measures the realization of blocking and all other variables are defined as above.

In case that realized blocking is sufficiently high Proposition 2 predicts that firms will prefer to enter into an ex post licensing contract to resolve blocking:

Hypothesis 4

$\beta_p^B > 0$.

5 Definition of Variables and Descriptive Statistics

In this section we describe variables employed in our model and provide further descriptive statistics. We also derive the econometric specification of the empirical model and consider issues that arise in estimation. The data used to construct variables are described in Appendix C. All variables characterize pairs of licensing firms. Variables are computed as the average or differences of the individual firms' characteristics where appropriate. Descriptive information for all variables is provided in Table 3. Below we discuss variables which do not appear in the bivariate probit selection model, but are used in a further test of our theoretical predictions.

As discussed above, ex ante licensing contracts grant firms the right to employ the licensee's future patents on a specific technology for a specific period. Ex post licensing contracts grant rights to use the licensee's patents for existing technologies.[11] The year in which a contract is signed determines the year for which almost all of our variables are generated. Our data set covers the period 1989 until 1999. For the sake of notational convenience we drop subscript t. Specific exceptions are discussed below. The timing for the licensing and blocking variables is discussed in detail in this section. Note that all our variables are defined in firm-pairs and on an annual basis.

Dependent Variables - Π_a, Π_p, A

Π_a measures whether a firm pair entered into an ex ante licensing contract ($\Pi_a = 1$) or not: If not, Π_p measures whether the firms entered into an ex post contract ($\Pi_p = 1$). A measures the number of patent applications in a given year.

Realized Blocking - B

Our theoretical model shows that the decision to sign an ex post licensing contract depends on the contemporaneously realized blocking measure, B. This variable measures the strength of

[11] For more detailed information on ex ante and ex post licensing contracts, see Appendix B and C.

technological rivalry between firms and the potential for hold-up. To capture these two dimensions of blocking we construct a measure of technological similarity (S^{ij}) between firms and a measure of citation intensity (C^{ij}). We define blocking as the interaction of these measures.

Technological similarity is measured as the uncentered correlation coefficient of the two firms' patent applications in a given year across nine patent classes,[12] to which all semiconductor patents may be assigned. The definition of this measure is:

$$S^{ij} = \frac{\sum_{c=1}^{9} A^{ic} A^{jc}}{\sqrt{\sum_{c=1}^{9} A^{ic}} \sqrt{\sum_{c=1}^{9} A^{jc}}} , \tag{5}$$

where A^{lc} is the number of patent applications by firm $l \in \{i, j\}$ in patent class c. The measure is widely used to capture technological proximity in the literature on patents (Jaffe, 1986).

Citation intensity is measured as the share of citations on the patents of firm i that point to patents belonging to firm j given a total of K firms cited by i:

$$C^{ij} = \frac{c^{ij}}{\sum_k c^{ik}}$$

where $k \in K$ and c^{ik} is the number of citations of firm k by firm i. Blocking is defined as:

$$B = \left(C^{ij} + C^{ji}\right) S^{ij} .$$

This measure is greater if two more technologically similar firms cite each others' patents more often. In this case we expect that blocking of one firm's activities by the other is more likely. Table 3 below shows that this measure of blocking is highest on average where firms chose ex post licensing and lowest where they did not license at all.

Expected Blocking - EB

The decision to license ex ante depends on firms' expectations of blocking. Since we do not observe firms' expectations of blocking we proxy these with the realization of blocking in the previous period. By assuming that an expectation for blocking in $t + 1$ is formed on the basis of current blocking levels, we assume that the time lag between decisions on ex ante and ex

[12] These patent classes are identified by Hall et al. (2005) as the classes $257,\ 326,\ 438,\ 505$ (semiconductors), $360,\ 365,\ 369,\ 711$ (memory) and 714 (microcomponents).

post licensing (see Figure 1) is one year.[13]

Table 3: Sample Statistics for Firm Pairs

Variable		Ex ante licensing Mean	Ex post licensing Mean	No licensing Mean	Full sample Mean	Std. dev.	Min.	Max.
Ex ante licensing	Π_a	1	0	0	0.007	-	0	1
Ex post licensing	Π_p	0	1	0	0.008	-	0	1
Patent applications	A	128.452	126.002	97.662	98.105	91.824	0	790
Expected blocking	EB	0.007	0.009	0.004	0.004	0.009	0	0.369
Blocking	B	0.007	0.011	0.005	0.005	0.010	0	0.216
Average patent stock	PS	530.876	474.633	371.256	373.198	424.330	0	4968
Difference in patent stocks	PS	632.016	542.755	483.115	484.627	570.965	0	5630
Fragmentation	PS	0.818	0.874	0.672	0.675	0.844	0	1.992
Average market shares	PM	0.030	0.030	0.024	0.024	0.019	0	0.108
Difference in market shares	PM	0.030	0.027	0.030	0.030	0.026	0	0.164
Multimarket participation	PM	1.640	1.599	1.509	1.511	0.512	1	3
Previous ex post contracts	L_A	6.702	7.925	6.090	6.110	6.896	0	51
Previous ex ante contracts	L_P	9.538	7.350	6.949	6.970	5.825	0	37
1990		0.080	0.136	0.081	0.081	-	0	1
1991		0.184	0.139	0.176	0.176	-	0	1
1992		0.188	0.286	0.267	0.266	-	0	1
1993		0.116	0.041	0.126	0.126	-	0	1
1994		0.128	0.136	0.154	0.153	-	0	1
1995		0.072	0.085	0.073	0.073	-	0	1
1996		0.096	0.024	0.018	0.018	-	0	1
1997		0.068	0.037	0.036	0.036	-	0	1
1998		0.028	0.024	0.023	0.023	-	0	1
NOBS		250	294	35,731	36,275			

To clarify the timing structure consider the case in which firms decide whether to license ex ante in period t - firms are at the start of the time path in Figure 1. The expectation of blocking is then formed for period $t+1$ and is proxied by the degree of blocking in period t. Now consider the case in which firms decide against ex ante licensing in period $t-1$. Then, in

[13] We tested for longer time lags with regard to the decision between ex ante and ex post licensing. Results are not significantly affected. Expectations based on longer time lags have weaker effects on firms' choices.

period t they decide between no licensing or ex post licensing. If we observe ex post licensing or no licensing in period t, we assume that firms decided not to engage in ex ante licensing in period $t-1$. We construct firms' expectations of blocking, which affected this decision not to license ex ante on the basis of observed blocking in period $t-2$.

Table 3 shows that the measure of expected blocking is higher for those firm-pairs that decided to license ex ante than for those that decided not to license. It is highest for firm-pairs that decided to license ex post.

Robustness Check for the Blocking Measure The blocking measures we describe above are proxies for blocking. We have no direct measures of litigation or of cease and desist letters which would capture how serious the threat of hold-up really is for each firm pair.

In order to provide additional evidence that the proposed blocking variables are appropriate proxies to measure the strength of blocking, we use additional information from European patent data. We identify European semiconductor patents that are equivalents for all the US semiconductor patents we have included in our data set.[14] Every European patent provides information on any previous patents which reduce the scope of protection for the patent under consideration. References to these patents are called X and Y references and they are determined by the patent examiner, which increases the objectivity of the information. This information is used by von Graevenitz et al. (2007) and von Graevenitz et al. (2008) to identify patent thickets.

Using this information, we generate a count of the number of blocking patents for each firm pair and construct alternative measures of blocking. We consider contemporaneous counts as well as the stock of patents with X and Y references and a discounted stock of these patents. The correlation between the blocking measure used in the principal analysis and the blocking measures we describe here is always in the medium range (> 0.3) and significantly different from zero. Appendix A provides results from the estimation of our main model using these alternative measures of blocking.

Product Market Competition - PM

We control for the effects of product market competition on firms' licensing choices. We use three measures to do this:

[14] To identify the equivalent patents we use a data set provided by Dietmar Harhoff. More information on this data set is provided in Graham and Harhoff (2006).

Average Market Shares We use the average market share of each firm pair in semiconductor product markets to control for importance of the firm pair within the semiconductor industry. Larger firms are more likely to have larger production facilities and are more susceptible to hold-up than firms that do not have such facilities (Hall and Ziedonis, 2001). Moreover, Stuart (1998) shows that firms with more prestige in the semiconductor industry are more likely to form alliances.[15] His measure of prestige is highly correlated with firm size. Table 3 shows that firm pairs that license have larger market shares on average than firm pairs that do not.

Difference in Market Shares This variable measures firm size asymmetries for each firm pair. Differences in firm size may reduce the propensity of firms to enter into licensing contracts if size proxies the prestige of each firm in a pair (Stuart, 1998). Descriptive statistics show the difference in market shares is similar for licensing and non-licensing pairs.

Multi-market Participation We control for the number of different product markets within the semiconductor industry in which firms have positive market share. We distinguish between microcomponents, memory chips and other devices. Firms active in several product markets are exposed to more competitors in technology space. The descriptive statistics indicate firms in licensing pairs are somewhat more diversified than firms in non licensing pairs.

Patent Stocks - PS

We also control for firms' relative strength in technology markets and the degree of fragmentation of these markets. To do this we use three different patent stock measures:

Average Patent Stock This is a measure of the size of firms' joint patent stocks. Table 3 reveals licensing firms tend to have larger patent stocks than non licensing firms.

Difference in Patent Stocks This measure controls for differences in the size of firms' patent stocks. On average the difference in patent stocks is largest for licensing firms.

Fragmentation Ziedonis (2004) shows that firms exposed to technology competition with more rival firms increase their patenting efforts. She shows this is particularly true for semiconductor firms with large production facilities. To control for the number of competitors who

[15] His definition of alliances subsumes licensing agreements as well as other forms of cooperation.

might hold-up a firm she controls for the fragmentation of a firm's patent citation stock. We include the measure as firms' propensity to enter into licensing contracts could decrease if the number of firms that might hold them up increases. We use the patent citation stock between two firms at the period of time at which they make their licensing decision and apply the correction suggested in the appendix of Hall et al. (2005) to control for bias resulting from low counts. Table 3 shows that fragmentation is on average greater for firm pairs that engage in licensing.[16]

Transaction Costs for Ex ante and Ex post Licensing - L_A, L_P

As noted above firms' previous experience with licensing will reduce costs of each subsequent contract. We control for experience of ex ante and ex post licensing separately as these types of contracts are usually structured differently. On average, firms that engaged in licensing have slightly higher previous experience of licensing than firms that did not engage in licensing.

Model Specification and Estimation

In the following, we estimate a bivariate probit selection model and a treatment effects model. We comment on the specification of the bivariate probit selection model and discuss how we constructed the sample of firm pairs.

The Bivariate Probit Selection Model The model takes the following form:

$$\Pi_a^* = \alpha_a + \beta_a^{EB} EB + \boldsymbol{\beta}_a^{PM} \boldsymbol{PM} + \boldsymbol{\beta}_a^{PS} \boldsymbol{PS} + \beta^{LA} L_A + \beta^{LP} L_P + \epsilon \tag{6}$$

$$\Pi_p^* = \alpha_p + \beta_p^{B} B + \boldsymbol{\beta}_p^{PM} \boldsymbol{PM} + \boldsymbol{\beta}_p^{PS} \boldsymbol{PS} + \beta_p^{LP} L_P + \eta$$

$$\Pi_a = \begin{cases} 1 & \text{if} \quad \Pi_a^* > 0 \\ 0 & \text{if} \quad \Pi_a^* \leq 0 \end{cases} \qquad \Pi_p = \begin{cases} 1 & \text{if} \quad \Pi_p^* > 0 \\ 0 & \text{if} \quad \Pi_p^* \leq 0 \end{cases}.$$

We estimate the selection and outcome equations of this model jointly by FIML.

The Sample To estimate the model (6), we use all firms that had positive market shares in the semiconductor industry between 1989 and 1999 in our data set. The restriction of our sample to firms with positive market shares in the semiconductor industry reduces the number

[16] The mean of the fragmentation index in our data lies in between the values reported by Ziedonis (2004) for the two samples she uses.

of licensing contracts to, 250 ex ante and 294 ex post licensing contracts. These are a subset of the licensing contracts we describe in section 2. There are $36,275$ firm-pair observations in the sample: each pair arising in years in which both firms had positive market shares.

6 Results

In this section we present results from the bivariate probit selection model presented in Section 4. We test exclusion restrictions derived from theory and restrictions suggested by our results. Then, we derive a switching model and present the results. This model provides an additional test our patent portfolio race model. Finally, the empirical results are discussed.

6.1 Effects of Blocking on Licensing

Which factors determine whether a firm pair engages in ex ante or ex post licensing? We predict that a higher expected blocking and greater experience of ex ante licensing raises the probability of observing ex ante licensing. Moreover, a higher realized blocking raises the probability of observing ex post licensing. To test these predictions the bivariate probit selection model discussed above, see equation (6), is estimated. Table 4 provides results of two specifications for this model. Table 5 sets out marginal effects for our preferred specification.

The results reported in Table 4 confirm the theoretical predictions: expected blocking increases the probability of ex ante licensing significantly and experience of ex ante (ex post) licensing raise (lower) the probability of ex ante licensing. Similarly, higher realizations of blocking raise the probability of observing ex post licensing. Coefficients and marginal effects for these variables are highly significant.

Table 4 provides two alternative specifications of the bivariate probit selection model. Columns (1) and (2) report a model that includes the expectation of blocking as an additional control variable in the outcome equation. Columns (3) and (4) report the same model without expected blocking in the outcome equation.

Based on our theoretical model, we predict that expected blocking acts as an exclusion restriction providing identification for the bivariate probit selection model. The presence of additional exclusion restrictions in the model allow us to test the validity of this prediction. Column (1) of Table 4 shows expected blocking is not significant in the outcome equation of the sample selection model. A likelihood ratio test comparing the two bivariate probit models reveals that expected blocking is a valid exclusion restriction ($\chi^2(1) = 1.25$). Therefore, we prefer the model presented in columns (3) and (4).

Table 4: Coefficients for Bivariate Probit Selection Models of Licensing

Independent Variable	Bivariate Probit		Bivariate Probit	
	Pr (Ex post)	Pr (Ex ante)	Pr (Ex post)	Pr (Ex ante)
	(1)	(2)	(3)	(4)
Blocking	9.802***		11.812***	
	(2.483)		(1.661)	
Expected blocking	3.549	6.612**		5.581*
	(3.174)	(3.047)		(2.909)
Average patent stock		-0.0002**		-0.0002**
		(0.00009)		(0.00001)
Differences in patent stocks	8.0·e-05**	5.0·e-05	10.0·e-05**	-5.0·e-05
	(4.0e-05)	(5.0e-05)	(4.0e-05)	(5.0e-05)
Fragmentation	-0.061*	-0.097**	-0.051*	-0.088**
	(0.032)	(0.044)	(0.031)	(0.043)
Average market shares	7.956***	4.665**	8.068***	4.737***
	(1.335)	(1.844)	(1.330)	(1.841)
Differences in market shares	-5.594***	-3.456***	-5.647***	-3.477***
	(0.940)	(1.179)	(0.940)	(1.180)
Multimarket participation	-0.017*	0.042	-0.018	0.041
	(0.049)	(0.063)	(0.049)	(0.063)
Previous ex post contracts		-0.017***		-0.018***
		(0.004)		(0.004)
Previous ex ante contracts		0.052***		0.052***
		(0.009)		(0.009)
Year dummies	YES	YES	YES	YES
Constant	-2.336***	-2.862***	-2.324***	-2.854***
	(0.115)	(0.159)	(0.115)	(0.159)
ρ	-0.976***		-0.975***	
	(0.0175)		(0.02)	
$-\ln L$	2613.175		-2613.799	

NOBS total=30,905, NOBS ex ante licensing=212, NOBS ex post licensing=261.

Standard errors in parentheses: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Evidence of sample selection is strong in both models as the correlation coefficient ρ is significant and negative. Note that the correlation coefficient is significantly different from one. The strong negative correlation suggests that unobserved random factors which lower the probability of ex ante licensing increase the probability of ex post licensing. This seems plausible given our theoretical framework: shocks that lead firms to avoid ex ante licensing in the face of high expected blocking, for instance poor information on expected blocking, will raise the likelihood that ex post licensing is necessary to resolve blocking ex post.

We test our preferred model against several further specifications: (i) we include previous ex post licensing in the outcome equation ($\chi^2(1) = 0.57$) and we also include both previous ex post and ex ante licensing in the outcome equation ($\chi^2(1) = -5.73$). In both cases we can clearly reject these alternative specifications. Therefore, Hypothesis 3 is not confirmed in our data set: costs of licensing ex post are insignificant in the ex post licensing decision. In contrast, Hypothesis 1 states that experience with ex ante (ex post) licensing will increase (reduce) the probability of ex ante licensing. This hypothesis is confirmed: coefficients and marginal effects on these variables are highly significant in the selection equation (4).

More importantly, Hypothesis 2 is confirmed. Table 5 shows that the marginal effect of expected blocking is significant at the 10% level. Moreover, Hypothesis 4 is confirmed: realized blocking significantly raises the probability of ex post licensing. These findings show that blocking patents determine licensing which supports our model of patent portfolio races.

Results reported in Table 4 show that variables which control for firms' importance in semiconductor product markets are highly significant in determining ex ante and ex post licensing. Larger and more symmetrical firm pairs are more likely to license ex ante. In contrast, pairs with larger average patent portfolios are less likely to license ex ante.

How important are these factors in determining licensing? The conditional probability of observing ex ante licensing based on our preferred model is quite low: 0.0054. The conditional probability of ex post licensing is 0.0071. These low probabilities result from the large number of firm pairs in the semiconductor industry which do not license. A one standard deviation increase in the expectation of blocking raises the probability of observing ex ante licensing by 0.0009 at the mean. This is an increase of 17% in the probability of ex ante licensing. A one standard deviation increase in market shares of a firm pair raises the probability of observing ex ante licensing by 0.0011, an increase of 20%. Table 5 shows that a one standard deviation increase in symmetry of firms in a pair has a comparable effect on the probability of observing ex ante licensing: it increases by 0.001 (19%). An increase in the size of the joint patent stock of a firm pair by one standard deviation reduces the probability of observing ex ante licensing by 0.0012 (21%). All of these effects are substantial. Turning to the fragmentation of firms patent citations we observe that this variable increased by over 0.4 over the sample period. This corresponds to a smaller probability of observing ex ante licensing of 10%. Finally, additional experience of one previous ex ante contract increases the probability of observing ex ante licensing by 16% while previous experience of ex post licensing reduces it by 5%.

Table 5: Marginal Effects for the Bivariate Probit Selection Model

	Bivariate probit	
Independent Variable	Pr (Ex post) (1)	Pr (Ex ante) (2)
Blocking	0.375***	
	(0.053)	
Expected blocking		0.087*
		(0.045)
Average patent stock		-3.13e-06***
		(1.48e-06)
Differences in patent stock	2.62e-06**	7.32e-07
	(1.2e-06)	(8.29e-07)
Fragmentation	-0.0016*	-0.001**
	(0.0009)	(0.006)
Average market shares	0.256***	0.073**
	(0.043)	(0.028)
Differences in market shares	-0.179***	-0.054***
	(0.029)	(0.018)
Multimarket participation	-0.0006	0.0006
	(0.059)	(0.0009)
Previous ex post contracts		-0.00027***
		(0.00006)
Previous ex ante contracts		0.0008***
		(0.00013)

NOBS total=30,905, NOBS ex ante licensing=212, NOBS ex post licensing=261.

Standard errors in parentheses: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

These results demonstrate that expected blocking has important effects on firms' propensity to license ex ante. Additionally, we find that ex ante licensing matters especially for large firm pairs in which partners are symmetrical. If firms have large patent portfolios they are less inclined to engage in ex ante licensing. More importantly, perhaps, we find that the trend towards greater fragmentation of patent citations undermines ex ante licensing significantly.

This shows that as the potential for hold up grows due to greater fragmentation of patent ownership, ex ante licensing is less useful in preventing hold-up.

The probability of observing ex post licensing rises by 0.0038 (54%) if blocking increases by one standard deviation at the mean. An increase in market shares by one standard deviation raises the probability of ex post licensing by 0.003 (43%). Increasing symmetry of market shares by one standard deviation raises this probability by 0.0033 (47%).

These effects are larger than those reported for the ex ante licensing decision. Ex post licensing is an important mechanism for firm pairs that have not licensed ex ante but find that they block each others patents to a significant degree. Especially larger and more symmetrical firm pairs resolve this problem by licensing ex post. Increasing fragmentation of patent citations also has a significant marginal effect on the ex post licensing decision. The sign of the coefficient indicates that ex post licensing is less likely as fragmentation increases.

Our results underline that licensing in the patent thicket is primarily important for large, symmetric firm pairs and is used to resolve potential hold-up. Overall the empirical results confirm semiconductor firms behave as if they are competing in patent portfolio races. We turn now to consider the effects of ex ante licensing for the level of patent applications made by a firm pair. This provides an additional test of the patent portfolio race model.

As noted above, we undertake a robustness check for these results to determine whether our main findings can be supported, if a different measure of blocking is used. These results are provided in Appendix A. There we show that we cannot reject any of the hypotheses tested in this section using the alternative measure of blocking. This gives us additional confidence in the results presented here.

6.2 Effects of Licensing on Patenting

Proposition 3 indicates firms' R&D investments will be higher under ex post licensing than under ex ante licensing. Here, we derive a switching model to test the following hypothesis:

Hypothesis 5

Patenting levels of firms that license ex ante will be lower than patenting levels of firms that license ex post.

Derivation of a Switching Model to Explain Patenting Levels

Now consider the level of patenting chosen by semiconductor firms. Our model indicates that the kind of licensing contract chosen by firms affects the intensity of patent portfolio races. We discuss an empirical model with which we test this implication of our theoretical model.

Using the switching model we treat the decision to license ex ante as an endogenous binary variable. Just like the bivariate probit selection model the switching model consists of two stages. We explain ex ante licensing using the selection equation (2) of the bivariate probit selection model. This equation is jointly estimated with an outcome equation for patenting levels in firm pairs.

Firms decide on the level of patent applications independently. Our empirical specification for the treatment model preserves the logic of modeling the behavior of firm pairs to make it comparable to the bivariate probit selection model. The dependent variable in the outcome equation of the switching model is the sum of patent applications in each firm pair. Accordingly, firms' joint level of patent applications A is determined as follows:

$$A = \beta_{os}^{c} + \beta_{os}^{D}\Pi_a + \beta_{os}^{B}B + \boldsymbol{\beta}_{os}^{PM}\boldsymbol{PM} + \boldsymbol{\beta}_{os}^{PS}\boldsymbol{PS} + \beta_{os}^{LP}L_P + \nu \quad , \tag{7}$$

where Π_a is the endogenous dummy variable capturing whether firms have licensed ex ante or not. All other variables are defined as previously. Identification of the switching model results from the same exclusion restrictions as in the bivariate probit selection model. Π_a is determined as set out in the bivariate probit selection model (6). The switching model is:

$$\begin{aligned} \Pi_a^* &= \beta_{as}^{c} + \beta_{as}^{EB}EB + \boldsymbol{\beta}_{as}^{PM}\boldsymbol{PM} + \boldsymbol{\beta}_{as}^{PS}\boldsymbol{PS} + \beta_{as}^{LA}L_A + \beta_{ps}^{LP}L_P + \epsilon \\ A &= \beta_{os}^{c} + \beta_{os}^{D}\Pi_a + \beta_{os}^{B}B + \boldsymbol{\beta}_{os}^{PM}\boldsymbol{PM} + \boldsymbol{\beta}_{os}^{PS}\boldsymbol{PS} + \beta_{os}^{LP}L_P + \nu \\ \Pi_a &= \begin{cases} 1 & \text{if} \quad \Pi_a^* > 0 \\ 0 & \text{if} \quad \Pi_a^* \leq 0 \end{cases} . \end{aligned} \tag{8}$$

This model is estimated by FIML.

Results from the Switching Model

Table 6 below sets out coefficients for the treatment effects model of patent applications. This table also contains marginal effects for the selection equation of the model. This equation is the same as in the bivariate probit selection model presented in Tables 4 and 5 and is estimated using the same sample of semiconductor firm pairs.

Table 6: Coefficients and Marginal Effects for the Switching Model

	Coefficients		Marginal effects
Independent Variable	Patent applications (1)	Pr (Ex ante) (2)	Pr (Ex ante) (3)
Ex ante licensing dummy	-12.551***		
	(4.323)		
Blocking	-435.949***		
	(24.596)		
Expected blocking		6.696**	0.101**
		(3.104)	(0.047)
Average patent stocks	0.194***	-0.0002	-3.48e-06*
	(0.001)	(0.0001)	(0.000)
Differences in patent stocks	0.008***	0.00003	4.18e-07
	(0.001)	(0.00006)	(0.000)
Fragmentation	16.137***	-0.100**	-0.002**
	(0.328)	(0.045)	(0.001)
Average market shares		3.391*	0.051*
		(1.869)	(0.028)
Differences in market shares		-3.294***	-0.050***
		(1.222)	(0.018)
Multimarket participation	6.491***	0.048	0.001
	(0.403)	(0.065)	(0.001)
Previous ex post contracts		-0.014***	-0.0002***
		(0.005)	(0.00007)
Previous ex ante contracts		0.062***	0.001***
		(0.010)	(0.0001)
Year dummies	YES	YES	
Constant	-84.392***	-3.055***	
	(1.303)	(0.194)	
ρ	0.126***		
	(0.043)		
σ	31.98***		
	(0.129)		

NOBS total=30,905, NOBS ex ante licensing=212, NOBS ex post licensing=261.

Standard errors in parentheses: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

The outcome equation (Column (1) in Table 6) of the switching model describes the joint level of patenting in a firm pair. We find that ex ante licensing has a significant negative effect on the patenting levels adopted by firms which contract ex ante. Such a contract reduces the size of the joint patent portfolio by 12.5 patents, a 13% reduction in the level of patenting. This result confirms the prediction of Proposition 3 and lends further support to the theoretical model of patent portfolio races derived above.

Additionally, we find a one standard deviation increase in blocking reduces firms' patenting by 4.36 patents. An increase in the patent stocks of firm pairs by one standard deviation raises patent application levels by 82 patents or 84%. Furthermore, confirming the findings in Ziedonis (2004) we show that greater fragmentation of patent citations increases patent applications. An increase in fragmentation by 0.4 raises patent applications by 6.5 patents $(6,5\%)$. Finally, market shares in the semiconductor industry have no effects on the level of patent applications but it does matter whether a firm is present in several product markets. Presence in an additional market raises joint patent applications by 6.5 patents.

These results show that the reduction in patenting due to an ex ante licensing contract is important. Such contracts allow large firms facing similar large rivals in technology space to insure themselves against hold-up by these larger firms. It is interesting to note that firm pairs for whom mutual blocking is high also reduce their level of patenting somewhat. However, this effect is much weaker than that of ex ante licensing.

Our findings provide an interesting contrast between effects of size in technology and product space. Firms with large shares of semiconductor product markets are highly likely to engage in licensing. This confirms the importance of licensing for competition in product markets: firms with important production facilities rely on licensing to guarantee freedom to operate (Grindley and Teece, 1997).

In contrast, the size of firms' patent portfolios affects their propensity to patent significantly while having little or no direct effect on licensing. Only differences in firms' patent stocks affects the probability of ex post licensing.

7 Conclusion

In this paper we investigate the choice between ex ante and ex post licensing in an industry affected by a patent thicket. We use a data set containing information on semiconductor firms and their licensing and patenting behavior which we construct combining data from several sources. The aim of the study is to determine whether licensing is driven by the need to guarantee “freedom to operate” as suggested by Grindley and Teece (1997) and whether it allows firms to reduce the competitive pressure resulting from patent portfolio races.

This paper comprises a thorough descriptive analysis of licensing in the semiconductor industry. It shows that there is no obvious relation between patenting and licensing trends in the semiconductor industry: a finding that is surprising given that Grindley and Teece (1997) argue licensing is used mainly to avoid hold-up resulting from blocking patents. To better understand what the effects of the patent thicket on firms’ R&D incentives and their choices of licensing contracts are, we distinguish between ex ante and ex post licensing. We find that ex ante licensing was very popular amongst semiconductor firms before 1996, thereafter its popularity rapidly declined.

To explain the variation in firms’ choices between ex ante and ex post licensing we develop a theoretical model of licensing in the context of patent portfolio races. In this model licensing does not consist of technology exchange, rather it allows firms to reduce the threat of hold-up in patent thickets. We show that licensing choices made by such firms is consistent with a model of patent portfolio races in which licensing guarantees freedom to operate. We show the choice between ex ante and ex post licensing depends on the expectations and realizations of blocking. Additionally, we show that firms’ R&D efforts and patenting levels depend on expected blocking and the choice of licensing contract.

To test our model of technology competition and licensing we estimate two models: a bivariate probit sample selection model explaining selection into ex post licensing and a treatment effects model explaining the level of patent applications. Using both models we are able to test separate predictions of our theoretical model. We are unable to reject the main predictions of the model. Thus expected and realized blocking strongly affect firms’ propensity to engage in licensing. If firms license ex ante this reduces the level of patenting significantly. Additionally, we find that especially firms with large product market shares in the semiconductor product markets engage in licensing. These firms choose both ex ante and ex post licensing to a significantly higher degree than firms with low market shares. Asymmetry of market shares reduces the likelihood that firms engage in licensing. This also indicates that the ”freedom to operate” explanation of licensing is central to understand licensing in patent thickets. Interestingly, the size of firms’ patent portfolios does not affect their propensity to license. However, it does affect firms’ patenting levels. Finally, we find that the fragmentation of patent rights reduces firms’ propensity to license ex ante and ex post. Thus, a deepening of patent thickets resulting from more complex blocking relationships seems to undermine the usefulness of licensing to resolve blocking.

These results imply that licensing has important benefits for large firms in the semiconductor industry. Ex ante licensing reduces competitive pressure and the intensity of patent portfolio races if firms expect blocking to be high. As the theoretical model indicates, these are precisely the settings in which the pressure to patent is greatest. Ex post licensing allows firms at least to exchange blocking patents in settings in which patent portfolio races are less intense. Our results show clearly that ability to license is an acquired skill that helps firms regulate the intensity of competition for patents. This is especially true for ex ante licensing. Worryingly, our results also indicate that licensing becomes less important as patent ownership becomes more fragmented.

As patent thickets are likely to persist in the near future (von Graevenitz et al., 2008), further research on the effects of licensing in complex technology industries seems warranted. In future research we intend to focus on the impact of licensing has on product market competition.

References

ALBERT, M., D. AVERY, F. NARIN, AND P. MCALLISTER (1991): "Direct Validation of Citation Counts as Indicators of Industrially Important Patents," *Research Policy*, 20, 251–259.

ANAND, B. AND T. KHANNA (2000): "The Structure of Licensing Contracts," *The Journal of Industrial Economics*, XLVIII, 103–135.

BEATH, J., Y. KATSOULACOS, AND D. ULPH (1989): "Strategic R&D Policy," *The Economic Journal*, 99, 74–83.

BESSEN, J. AND M. J. MEURER (2008): *Patent Failure*, Princeton University Press.

CLARK, D. J. AND K. A. KONRAD (2008): "Fragmented Property Rights and Incentives for R&D," *Management Science*, 54, 969–981.

FEDERAL TRADE COMMISSION (2003): "To Promote Innovation: The Proper Balance of Competition and Patent Law and Policy," Tech. rep., FTC, http://www.ftc.gov/opa/2003/10/cpreport.htm.

FERSHTMAN, C. AND M. I. KAMIEN (1992): "Cross Licensing of Complementary Technologies," *International Journal of Industrial Organization*, 10, 329–348.

GALASSO, A. (2007): "Broad Cross-License Agreements andPersuasive Patent Litigation: Theory andEvidence from the Semiconductor Industry," Economics of Industry Papers 45, STICERD.

GRAHAM, S. AND D. HARHOFF (2006): "Can Post-Grant Reviews Improve Patent System Design? A Twin Study of US and European Patents," Working Paper 5680, CEPR.

GRINDLEY, P. C. AND D. J. TEECE (1997): "Managing Intellectual Capital: Licensing and Cross-Licensing in Semiconductors and Electronics," *California Management Review*, 39, 8–41.

HALL, B. H., A. B. JAFFE, AND M. TRAJTENBERG (2005): "Market Value and Patent Citations," *Rand Journal of Economics*, 36, 16–38.

HALL, B. H. AND R. ZIEDONIS (2001): "The Patent Paradox Revisited: An Empirical Study of Patenting in the U.S. Semiconductor Industry, 1979-1995," *Rand Journal of Economics*, 32, 101–128.

HARHOFF, D. AND S. WAGNER (2009): "The Duration of Patent Examination at the European Patent Office," *Management Science*, 55, 1969–1984.

HELLER, M. A. AND R. S. EISENBERG (1998): "Can Patents Deter Innovation? The Anticommons in Biomedical Research," *Science*, 280, 698–701.

HUYS, I., N. BERTHELS, G. MATTHIJS, AND G. V. OVERWALLE (2009): "Legal uncertainty in the area of genetic diagnostic testing," *Nature Biotechnology*, 27, 903–909.

JAFFE, A. B. (1986): "Technological Opportunity and Spillovers of R&D: Evidence from Firms' Patents, Profits and Market Value," *American Economic Review*, 76, 984–1001.

——— (2000): "The U.S. Patent System in Transition: Policy Innovation and the Innovation Process," *Research Policy*, 29, 531–557.

JAFFE, A. B. AND J. LERNER (2004): *Innovation and Its Discontents: How Our Broken Patent System is Endangering Innovation and Progress, and What to Do About It.*, Princeton, N.J.: Princeton University Press.

JORGENSON, D. W. (2001): "Information Technology and the U.S. Economy," *American Economic Review*, 91, 1–32.

LEE, T. AND L. L. WILDE (1980): "Market Structure and Innovation: A Reformulation," *The Quarterly Journal of Economics*, 94, 429436.

LEMLEY, M. (2001): "Rational Ignorance at the Patent Office," *Northwestern University Law Review*, 95, 1–39.

MASTEN, S. E. (1993): "Transaction Costs, Mistakes, and Performance: Assessing the Importance of Governance," *Managerial and Decision Economics*, 14, 119–129.

MILGROM, P. AND J. ROBERTS (1990): "Rationalizability, Learning and Equilibrium in Games with Strategic Complementarities." *Econometrica*, 58, 1255–1278.

REINGANUM, J. F. (1989): "The Timing of Innovation: Research, Development and Diffusion," in *Handbook of Industrial Organization*, ed. by R. Schmalensee and R. D. Willig, Amsterdam, Netherlands: Elsevier Science, vol. 1, 850–908.

ROWLEY, T., D. BEHRENS, AND D. KRACKHARDT (2000): "Redundant Governance Structures: An Analysis of Structural and Relational Embeddedness in the Steel and Semiconductor Industries," *Strategic Management Journal*, 21, 369–386.

SHAPIRO, C. (2001): "Navigating the Patent Thicket: Cross Licenses, Patent Pools, and Standard-Setting," in *Innovation Policy and the Economy*, ed. by A. B. Jaffe, J. Lerner, and S. Stern, Cambridge, Mass.: MIT Press, vol. 1, 119–150.

——— (2003): "Technology Cross-Licensing Practices: F.T.C. vs. Intel (1999)," in *The Antitrust Revolution*, ed. by J. E. Kwoka and L. J. White, Oxford: Oxford University Press, 350–369.

SHAVER, J. M. (1998): "Accounting for Endogeneity When Assessing Strategy Performance: Does Entry Mode Choice Affect FDI Survival?" *Management Science*, 44, 571 – 585.

SOMAYA, D. (2003): "Strategic Determinants of Decisions not to Settle Patent Litigation," *Strategic Management Journal*, 24, 17–38.

STUART, T. (1998): "Network Positions and Propensities to Collaborate: An Investigation of Strategic Alliance Formation in a High-technology Industry," *Administrative Science Quarterly*, 43, 668–698.

VILLALONGA, B. AND R. AMIT (2006): "How do Family Ownership, Management, and Control Affect Firm Value?" *Journal of Financial Economics*, 80, 385–417.

VIVES, X. (1999): *Oligopoly Pricing, Old Ideas and New Tools*, Cambridge, Massachusetts and London, England: MIT Press.

VON GRAEVENITZ, G., S. WAGNER, AND D. HARHOFF (2008): "Incidence and Growth of Patent Thickets - The Impact of Technological Opportunities and Complexity," CEPR Discussion Papers 6900, C.E.P.R. Discussion Papers.

VON GRAEVENITZ, G., S. WAGNER, K. HOISL, B. HALL, D. HARHOFF, P. GIURI, AND A. GAMBARDELLA (2007): *The Strategic Use of Patents and its Implications for Enterprise and Competition Policies*, Report for the European Commission.

VONORTAS, N. S. (2003): "Technology Licensing," Final report, Center for International Sceince and Technology Policy, The George Washington University, Washington D.C.

ZIEDONIS, R. H. (2003): "Patent Litigation in the U.S. Semiconductor Industry," in *Patents in the Knowledge-Based Economy*, ed. by W. M. Cohen, Washington, D.C.: National Academies Press, 180–215.

——— (2004): "Don't Fence Me In: Fragmented Markets for Technology and the Patent Acquisition Strategies of Firms," *Management Science*, 50, 804–820.

A Empirical Robustness Checks

Table 7 below sets out results analogous to those presented in Table 4 above. Here we replace the blocking variables derived from information about firms patenting behavior in the United States with a more direct measure of blocking derived from European patent data. To derive this alternative measure of blocking we exploit the equivalence of US and European patents.

Table 7: Coefficients for Bivariate Probit Selection Models of Licensing

Independent Variable	Bivariate Probit Pr (Ex post) (1)	Bivariate Probit Pr (Ex ante) (2)	Bivariate Probit Pr (Ex post) (3)	Bivariate Probit Pr (Ex ante) (4)
Blocking	0.196*		0.149**	
	(0.106)		(0.065)	
Expected blocking	-0.084	0.232***		0.233***
	(0.153)	(0.025)		(0.025)
Average patent stock		0.798e-04		0.799e-04
		(0.227e-03)		(0.225e-03)
Differences in patent stocks	0.141·e-03	0.152·e-03	0.185·e-03	0.154·e-03
	(0.211e-03)	(0.129e-03)	(0.169e-03)	(0.129e-03)
Fragmentation	0.055	0.033	0.043	0.033
	(0.158)	(0.081)	(0.148)	(0.081)
Average market shares	13.625	-4.427	12.965	-4.261
	(0.214)	(3.984)	(10.443)	(3.969)
Differences in market shares	0.383	5.556***	0.170	5.492***
	(5.378)	(2.196)	(5.183)	(2.189)
Multimarket participation	-0.738	0.387***	-0.675	0.387***
	(0.564)	(0.134)	(0.525)	(0.134)
Previous ex post contracts		-0.055***		-0.055***
		(0.011)		(0.011)
Previous ex ante contracts		0.023*		0.023*
		(0.013)		(0.013)
Constant	-2.202***	-2.810***	-2.215***	-2.815***
	(0.587)	(0.562)	(0.115)	(0.238)
ρ	-0.879***		-0.908***	
	(0.145)		(0.102)	
$-\ln L$	-373.169		-373.349	

NOBS total=2,745.

Standard errors in parentheses: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

These results confirm our earlier findings. Licensing experience and blocking carry the signs predicted by our model. We believe that this additional robustness check shows that the proxy of blocking which we derive from US patent data captures blocking quite well.

B A Model of Licensing in Patent Thickets

In this section, we derive the results discussed in Section 3. First the notation and our main assumptions are set out. Next, we derive the value of licensing ex post, given the degree of blocking. Then, the value of ex ante licensing is derived. We are able to provide comparative statics results for the model because firms' R&D investments are strategic complements and the game we analyze is smooth supermodular. In the final section of this appendix, we prove this result.

B.1 General Assumptions

To capture the effect of blocking on R&D competition we make two sets of assumptions: the first pertains to the timing of the model and clarifies why blocking arises; the second describes the nature of rivalry between firms through the form of their profit functions.

Consider timing first: two firms invest in a new technology. They begin to patent parts of the technology after a lag due to research into this technology. The date at which patenting begins depends on firms' research efforts. Firms invest to begin patenting first and the lead built up by the winner depends on its rival's research effort.

Figure 2 illustrates the timing of our model. Assume that the times at which the winner

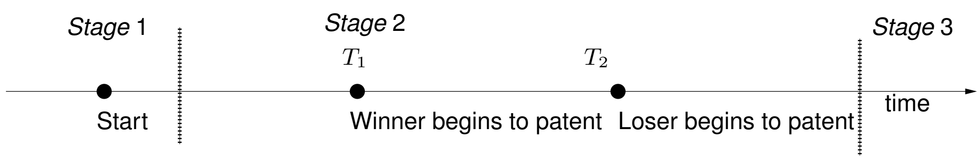


Figure 2: Time line for the patent portfolio race

and loser of the patent portfolio race start patenting (T_1, T_2), are randomly distributed with the exponential distribution:

$$Pr(t \leq T_1) = 1 - e^{-h_w T_1} \quad \text{and} \quad Pr(t \leq T_2) = 1 - e^{-h_l T_2} .$$

All variables pertaining to winner and loser are denoted with the subscripts $_{w,l}$ below. Here

h_l, h_w denote their hazard rates which capture research efforts. Note that T_1 and T_2 are independent. Then, duration of the period $T_2 - T_1$ depends on the loser's R&D investments.

We assume the period in which firms build patent portfolios in each technology is short enough that rivals' R&D efforts remain unobserved. Therefore, we adopt a model of R&D competition in which firms commit to R&D investments at the start of the game - firms apply open loop strategies. We embed the patent portfolio race in a three stage model of decisions on licensing:

Stage one: Both firms simultaneously choose whether to sign an ex ante licensing contract.

Stage two: Both firms invest in research and obtain patents.

Stage three: Firms choose whether to bargain over an ex post contract if they have not signed an ex ante contract.

This model is solved by backward induction.

Now consider firms' profits: firms are initially symmetrical and earn profits π_0. Profits depend on the size of patent stocks to the extent that these guarantee "freedom to operate". The winner's portfolio of patents consists of unblocked patents accumulated in the period before T_2 and of patents accumulated after T_2. The likelihood that one of these later patents is blocked is denoted β, where $\beta \in [0, 1]$. In the absence of a licensing contract the expected sizes of winner's (Q_w) and loser's (Q_l) portfolios of unblocked patents are:

$$Q_w(h_l, \beta, \lambda) = \int_{s=0}^{\infty} \lambda e^{-h_l s} e^{-rs} + \tfrac{\lambda}{r}(1-\beta) h_l e^{-h_l s} e^{-rs} ds = \frac{\lambda + \frac{\lambda}{r} h_l (1-\beta)}{h_l + r} \tag{9}$$

$$Q_l(h_l, \beta, \lambda) = \int_{s=0}^{\infty} \tfrac{\lambda}{r}(1-\beta) h_l e^{-h_l s} e^{-rs} ds = \frac{\frac{\lambda}{r} h_l (1-\beta)}{h_l + r} \quad , \tag{10}$$

where λ denotes the exogenous rate of patenting and r is the interest rate. h_l denotes the loser's research efforts. These expressions are derived by noting that the winner will patent at rate λ before and after T_2. The loser only patents at this rate after T_2. High research effort allows the loser to induce greater ex post symmetry between firms' patent portfolios.

Expected profits depend on the number of unblocked patents in each firm's own and in its rival's patent portfolios: $\pi_i(Q_i, Q_j)$ where $i; j$ are subscripts denoting the firm itself (i) and its rival (j). In particular, a firm's profits are increasing in the size of its own patent portfolio. Rivalry implies a negative effect of the size of the rivals' patent stocks on own profits. Finally, we assume both effects increase at decreasing rates:

$$\frac{\partial \pi_i(Q_i, Q_j)}{\partial Q_i} > 0, \quad \frac{\partial \pi_i(Q_i, Q_j)}{\partial Q_j} < 0, \quad \frac{\partial^2 \pi_i(Q_i, Q_j)}{\partial {Q_i}^2} < 0, \quad \frac{\partial^2 \pi_i(Q_i, Q_j)}{\partial {Q_j}^2} > 0. \tag{P}$$

We also assume that firms' profit functions are supermodular in patent portfolios:

$$\frac{\partial^2 \pi_i(Q_i, Q_j)}{\partial Q_i \partial Q_j} > 0 \quad . \tag{S}$$

This assumption implies that each firm's marginal benefit from additional patents is increasing in the size of their rival's patent portfolio. In patent portfolio races the relative size of firms' patent portfolios determines bargaining strength (Lemley, 2001). To capture this we assume that a marginal patent is more valuable if rivals' patent portfolios are greater. A simple example of a profit function which fulfills assumptions (P) and (S) is: $\pi_i = \log(Q_i) - \log(Q_i + Q_j)$. We impose standard restrictions on firms' R&D costs:

$$\text{(i) } \gamma(0) = \gamma'(0) = 0, \ \gamma''(0) > 0 \qquad \text{(ii) } \forall h > 0, \ \ \gamma(h) > 0, \ \gamma'(h) > 0, \ \gamma''(h) > 0$$
$$\text{(iii) } \lim_{h \to \infty} \gamma'(h) = \infty \quad . \tag{G}$$

This restrictions imply: (i) firms always do some R&D, (ii) the costs of R&D are strictly increasing in R&D efforts, (iii) no firm begins to patent with certainty in the following instant.

B.2 Ex post Licensing

An ex post licensing contract removes the threat of hold-up and provides firms with "freedom to operate". Then $\beta = 0$ and patent portfolios under the ex post contract are:[17]

$$\bar{Q}_w(\lambda) = \frac{\lambda}{r} = Q_w(h_l, 0, \lambda) \quad \text{and} \quad \bar{Q}_l(h_l, \lambda) = \frac{\lambda}{r} \frac{h_l}{h_l + r} = Q_l(h_l, 0, \lambda) \quad . \tag{11}$$

$\bar{Q}$ represents the upper bound of each firm's possible patent stock which is attained when blocking is zero. We assume that the licensing contract signed by the firms conforms to the Nash bargaining assumptions. This implies the party which has a stronger bargaining position receives some of the surplus generated by the licensing contract in the form of a payment.

[17] Contrast this with the case in which the firms exchange technologies. This would be the standard assumption in most models of licensing in the literature to date. Then both firms' patent stocks would comprise all new patents: $\bar{Q} = \frac{\frac{\lambda}{r}(2h_l + r)}{h_l + r}$.

Grindley and Teece (1997) confirm the existence of such payments as do our data. Under Nash bargaining the winner's and loser's payoffs are:

$$v_w = \frac{\triangle\pi}{2} + \frac{1}{2}\left[\pi(\bar{Q}_w, \bar{Q}_l) + \pi(\bar{Q}_l, \bar{Q}_w)\right] \qquad v_l = -\frac{\triangle\pi}{2} + \frac{1}{2}\left[\pi(\bar{Q}_w, \bar{Q}_l) + \pi(\bar{Q}_l, \bar{Q}_w)\right] \ , \quad (12)$$

where a winner's expected profits are $\pi(Q_w, Q_l)$ and a loser's profits are $\pi(Q_l, Q_w)$. Define $\triangle\pi \equiv (\pi(Q_w, Q_l) - \pi(Q_l, Q_w))$. Then: $v_w + v_l = \pi(\bar{Q}_w, \bar{Q}_l) + \pi(\bar{Q}_l, \bar{Q}_w)$ and $v_w - v_l = \triangle\pi$. The value function describing the expected return from a patent portfolio race is:[18]

$$\begin{aligned} V_p(\beta, \pi_0, h_p, H_p) &= \int_{u=0}^{\infty} e^{-ru}\left[\tfrac{v_w(H_p,\beta)}{r} h_p e^{-h_p u} + \tfrac{v_l(h_p,\beta)}{r} H_p e^{-H_p u} + (\pi_0 - \gamma(h_p))\, e^{-H_p u} e^{-h_p u}\right] du \\ &= \frac{\tfrac{v_w(H_p,\beta)}{r} h_p + \tfrac{v_l(h_p,\beta)}{r} H_p + \pi_0 - \gamma(h_p)}{h_p + H_p + r}, \end{aligned} \quad (13)$$

where $_p$ denotes ex post licensing. h_p is the hazard rate chosen by the investing firm and H_p the rival's hazard rate. This value function differs from patent race models in the tradition of Lee and Wilde (1980) as the expected values of winning and losing are also functions of firms' research efforts: the expected value of winning the patent portfolio race declines in the rival's investments (H_p) and the expected value of losing increases in own investments (h_p).

R&D Investment

The optimal hazard rate under ex post licensing solves the following optimisation problem:

$$\max_{h_p \geq 0} V_p(\beta, \pi_0, h_p, H_p) \qquad . \quad (14)$$

It can be shown that:

Proposition 4

The patent portfolio race defined by (14) is a smooth supermodular game.

To see this consider the first order condition and the cross-partial derivative with respect to the rival firm's R&D investment:

$$\frac{\partial V_p}{\partial h_p} = \frac{1}{(h_p + H_p + r)^2}\left[\underbrace{\frac{(v_w - v_l)}{r} H_p}_{\text{Comp. threat}} + \underbrace{[v_w - \pi_0]}_{\text{Profit in.}} + \underbrace{\frac{\partial v_l}{\partial h_p}\frac{H_p}{r}(h_p + H_p + r)}_{\text{Symmetry inc.}}\right.$$

[18] The derivation of this value function is analogous to that of value functions in patent race models such as Lee and Wilde (1980).

$$+\gamma(h_p)-\gamma'(h_p)\left[h_p+H_p+r\right]\Bigg]=0. \quad (15)$$

Three incentives determine each firm's patenting efforts. First the competitive threat, which captures the value of winning rather than losing, next the profit incentive, which captures the benefit of winning sooner rather than later.[19] Both of these incentives are positive here as winning the patent portfolio race enlarges the patent portfolios most and this increases profits by assumption (P). Finally, there is a symmetry incentive which captures the increased symmetry of winner and loser if the latter invests more. While the first two incentives are known (Reinganum, 1989; Beath et al., 1989), the third is new to our model. In Appendix B.4 we demonstrate that the symmetry incentive is positive.

Now consider the cross-partial derivative with respect to rivals' investments:

$$\frac{\partial^2 V_p}{\partial h_p \partial H_p}=\frac{1}{(h_p+H_p+r)^2}\left[\frac{(v_w-v_l)}{r}+\frac{\partial v_l}{\partial h_p}\frac{1}{r}(h_p+2H_p+r)+\frac{\partial v_w}{\partial H_p}\frac{1}{r}(H_p+r)-\gamma'(h_p)\right] \quad , \tag{16}$$

At B.4 below we demonstrate that this expression is positive. Therefore, the game defined above ((14)) is smooth supermodular (Milgrom and Roberts, 1990; Vives, 1999).

Next, consider the effects of an increase in blocking on the expected value of ex post licensing. We derive an intermediate result first:

Proposition 5

The value of ex post licensing decreases as firms' equilibrium R&D efforts increase.

Define $\hat{h}_p$ as the symmetric equilibrium solution to firms' optimization problem (14). Then, the expected value of ex post licensing in equilibrium (13) is:

$$V_p(\hat{h}_p)=\frac{\frac{v_w+v_l}{r}\hat{h}_p+\pi_0-\gamma(\hat{h}_p)}{2\hat{h}_p+r} \quad . \tag{17}$$

Differentiating this expression with respect to blocking we find the effect of blocking on the value of ex post licensing has two components:

$$\frac{\partial V_p(\hat{h}_p)}{\partial \beta}=-\frac{1}{2\hat{h}_p+r}\left[V_p-\frac{v_l}{r}+\left(\frac{\partial v_l}{\partial \hat{h}_p}-\frac{\partial \pi(\bar{Q}_l,\bar{Q}_w)}{\partial \hat{h}_p}+\frac{\partial \pi(\bar{Q}_w,\bar{Q}_l)}{\partial \hat{h}_p}\right)\frac{\hat{h}_p}{r}\right]\frac{\partial \hat{h}_p}{\partial \beta} \quad , \tag{18}$$

[19] The competitive threat is also referred to as the replacement effect, while the profit incentive is also called the efficiency effect.

The first component is the effect of greater R&D efforts on the expected value of ex post licensing. The second is the effect of blocking on firms' R&D incentives.

The expected value of ex post licensing is decreasing in the level of equilibrium R&D efforts. To see this consider the case in which there is no blocking. Then, the sum of derivative terms in equation (18) is $-\partial\pi(\bar{Q}_w, \bar{Q}_l)/\partial h_p > 0$. At B.5 we show that increased blocking raises marginal returns to R&D investments for the loser. Then, Equation (18) is positive at any level of blocking.

Turn now to the second component: to sign the effect of blocking on firms' R&D investments we derive the cross-partial effect of blocking and research efforts. Milgrom and Roberts (1990) show the sign of cross-partial effects determines the sign of a comparative statics effect in supermodular games. Given assumptions (S) and (P) we show that:

Proposition 6

Increases in blocking raise firms' equilibrium R&D efforts ($\hat{h}$).

The proof is relegated to Appendix B.5.

Propositions 5 and 6 together lead to Proposition 1. To see this, note that these propositions imply that more blocking lowers the expected value of ex post licensing (V_p). As we have shown greater blocking induces greater R&D efforts and these reduce the value of ex post licensing. Without further analysis of ex ante licensing we can infer that increases in blocking reduce the value of ex post licensing relative to ex ante licensing. To see this note that ex ante licensing by definition consists of a contract that prevents blocking. Therefore, variation in blocking has no effects on the value of ex ante licensing.

B.3 Ex ante Licensing

Under an ex ante licensing contract firms agree not to hold-up the rival, i.e. there is no blocking. Therefore, the expected size of the firms' patent portfolios are $\bar{Q}_w$ and $\bar{Q}_l$. Then, the analysis of firms' R&D incentives under ex ante licensing is analogous to that of ex post licensing. In particular it follows that:

Proposition 7

If firms expect zero blocking, ex ante and ex post licensing are worth the same: $V_a = V_p$.

This proposition implies that firms will strictly prefer ex post licensing to ex ante licensing if there are positive costs of licensing. Under ex ante licensing such costs must be payed with certainty, whereas under ex post licensing such costs would be borne only with a probability strictly less than one, if expected blocking is zero. We show this below.

To see that Proposition 7 holds consider the value function firms under ex ante licensing:

$$V_a(0, \pi_0, h_a, H_a) = \frac{\frac{v_w(H_a,0)}{r} h_a + \frac{v_l(h_a,0)}{r} H_a + \pi_0 - \gamma(h_a)}{h_a + H_a + r} \quad . \tag{19}$$

By analogy the first order condition determining the equilibrium hazard rate $\hat{h}_a$ is:

$$\frac{\partial V_a}{\partial h_a} = \frac{1}{(h_a + H_a + r)^2} \Bigg[\underbrace{\frac{(v_w - v_l)}{r} H_a}_{\text{Comp. threat}} + \underbrace{[v_w - \pi_0]}_{\text{Profit inc.}} + \underbrace{\frac{\partial \pi(\bar{Q}_l, \bar{Q}_w)}{\partial h_a} \frac{H_a}{r} (h_a + H_a + r)}_{\text{Symmetry inc.}} + \gamma(h_a) - \gamma'(h_a) [h_a + H_a + r] \Bigg] = 0 \quad . \tag{20}$$

Given this expression, it can be seen that the R&D investment game firms play under an ex ante contract is also smooth supermodular. Equation (20), shows that ex ante licensing is just a form of ex post licensing in which there is no threat of blocking. Then, Proposition 3 follows from Proposition 6 as blocking is lowest under ex ante licensing.

This result does not arise from underinvestment which is usually associated with R&D cooperation. Note that we do not consider technology transfer here. Rather, as Proposition 6 shows, increases in blocking have the effect of strengthening firms' R&D incentives under ex post licensing. By implication R&D incentives under ex ante licensing are weaker than those under ex post licensing which leads to lower levels of patenting.

This model shows how the expectation of blocking affects firms' licensing behavior. In the following section we derive an empirical model to test Propositions 1 and 3.

B.4 Supermodularity of the Patent Portfolio Race

In this section we demonstrate that the cross-partial derivative in equation (16) is positive and that blocking raises firms' equilibrium R&D incentives.

To demonstrate supermodularity we show first that the symmetry incentive is positive:

$$\frac{\partial v_l}{\partial h_p} = \frac{\lambda}{2(h_p + r)^2} \Big[\frac{\partial \pi(Q_l, Q_w)}{\partial Q_l} \beta - \frac{\partial \pi(Q_l, Q_w)}{\partial Q_w} (1-\beta) + \frac{\partial \pi(Q_w, Q_l)}{\partial Q_w} (1-\beta) - \frac{\partial \pi(Q_w, Q_l)}{\partial Q_l} \beta + \frac{\partial \pi(\bar{Q}_l, \bar{Q}_w)}{\partial \bar{Q}_l} + \frac{\partial \pi(\bar{Q}_w, \bar{Q}_l)}{\partial \bar{Q}_l} \Big] > 0 \quad . \tag{21}$$

This expression is positive. To see this note that in the absence of blocking $v_l = \pi(\bar{Q}_l, \bar{Q}_w)/r$. Greater R&D effort ($h_p$) increases the size of the loser's patent portfolio Q_l and their expected profits. Therefore, (21) is positive when there is no blocking. Supermodularity of the profit function and assumption (P) imply that greater blocking increases the marginal value of R&D investment to the loser. This is shown below in Section B.5. R&D investment brings forward the date at which the loser begins to patent and enhances their bargaining position. Therefore, the expression is positive for all values of β.[20]

Now consider the cross-partial derivative w.r.t. firms' own and rivals' R&D investments. We show next that this derivative is positive:

$$\frac{\partial^2 V_p}{\partial h_p \partial H_p} = \frac{1}{(h_p + H_p + r)^2}\left[V_p - \frac{v_l}{r} + \frac{\partial v_l}{\partial h_p}\frac{1}{r}(h_p + H_p + r) + \frac{\partial v_w}{\partial H_p}\frac{1}{r}(H_p + r)\right] > 0 \quad . \tag{22}$$

Here, we have made use of the first order condition (15) to substitute out terms. Then we insert V_p as defined in equation (13). Now, consider the term in brackets: the difference of the first two terms must be positive otherwise R&D investment would not pay off. The sum of the remaining terms is also positive. Given the definitions of v_w and v_l (12) it is apparent that:

$$\frac{\partial v_l}{\partial h_p} = -\frac{\partial v_w}{\partial H_p} \quad . \tag{23}$$

Therefore, if the symmetry incentive is positive, so is (22).

B.5 Effects of Blocking on R&D Investment

Now consider the effect of blocking on the marginal value of own R&D investment:

$$\frac{\partial^2 V_p}{\partial \hat{h} \partial \beta} = \frac{1}{(2\hat{h} + r)}\left[\frac{\partial \triangle \pi}{\partial \beta}\frac{(\hat{h} + r)}{(2\hat{h} + r)} + \frac{\partial^2 v_l}{\partial h_p \partial \beta}\frac{\hat{h}_p}{r}\right] \quad . \tag{24}$$

[20] As an example consider once more the supermodular profit function: $\pi_i = log(Q_i) - log(Q_i + Q_j)$. Then it is easily shown that $\frac{\partial \pi(\bar{Q}_l, \bar{Q}_w)}{\partial \bar{Q}_l} + \frac{\partial \pi(\bar{Q}_w, \bar{Q}_l)}{\partial \bar{Q}_l} = \frac{Q_w - Q_l}{Q_l(Q_l + Q_w)} > 0$.

If firms' profit functions are supermodular, then we can show that $\frac{\partial \triangle \pi}{\partial \beta} > 0$ and $\frac{\partial^2 v_l}{\partial h_p \partial \beta} > 0$:

$$\frac{\partial \triangle \pi}{\partial \beta} = -\frac{\lambda}{2r} \frac{\hat{h}_p}{\hat{h}_p + r} \Big[\underbrace{\frac{\partial \pi(Q_w, Q_l)}{\partial Q_w} + \frac{\partial \pi(Q_w, Q_l)}{\partial Q_l} - \frac{\partial \pi(Q_l, Q_w)}{\partial Q_l} - \frac{\partial \pi(Q_l, Q_w)}{\partial Q_w}}_{\nu} \Big] \tag{25}$$

$$\begin{aligned}\frac{\partial^2 v_l}{\partial h_p \partial \beta} =& \frac{\lambda}{2(h_p + r)^2} \Big[\underbrace{\frac{\partial \pi(Q_l, Q_w)}{\partial Q_l} + \frac{\partial \pi(Q_l, Q_w)}{\partial Q_w} - \frac{\partial \pi(Q_w, Q_l)}{\partial Q_w} - \frac{\partial \pi(Q_w, Q_l)}{\partial Q_l}}_{-\nu} \Big] \qquad (26) \\ & - \frac{\lambda^2}{2r(h_p + r)^3} \Bigg[\underbrace{\frac{\partial^2 \pi(Q_l, Q_w)}{\partial {Q_l}^2} \beta - \frac{\partial^2 \pi(Q_l, Q_w)}{\partial {Q_w}^2}(1-\beta) + \frac{\partial^2 \pi(Q_w, Q_l)}{\partial {Q_w}^2}(1-\beta) - \frac{\partial^2 \pi(Q_w, Q_l)}{\partial {Q_l}^2} \beta}_{\omega} \\ & \underbrace{- \frac{\partial^2 \pi(Q_l, Q_w)}{\partial Q_w \partial Q_l}(1 - 2\beta) + \frac{\partial^2 \pi(Q_w, Q_l)}{\partial Q_w \partial Q_l}(1 - 2\beta)}_{\zeta} \Bigg]\end{aligned}$$

Supermodularity of the profit function implies that the third element of ν is larger than the first and the second is larger than the fourth. If firms *compete*, i.e. $\frac{\partial \pi(q_i, q_j)}{\partial q_j} < 0$ then $\nu < 0$ and $\frac{\partial \triangle \pi}{\partial \beta} > 0$. Assumption (P) also implies that ω is negative. Finally, local stability of equilibrium requires that the cross partial effects (ζ) are smaller in absolute value than the second derivatives that are components of ω. Therefore, even if one or the other of these cross partial effects is positive we have shown that overall $\frac{\partial^2 v_l}{\partial h_p \partial \beta} > 0$: greater blocking induces firms to invest more effort in R&D as blocking increases.

C Data Sources

This section provides details about the origin of our data on licensing, patents and market shares in the semiconductor industry.

C.1 Licensing

The basis of our data on licensing contracts was provided by Thompson Financial. We complemented this with information derived from sources in the public domain such as business reports, filings published in the National Cooperative Research Act, and announcements made in the public press.

The data set covers licensing contracts in which at least one party has a principal line of business in the semiconductor industry between 1989-1999. All such firms for which annual semiconductor market shares were available during the period 1989-1999 were included in the sample. This sampling criterion was imposed because firms' product market positions are an important variable in our theoretical as well as statistical model. We identified name changes and subsidiaries and mergers from a variety of sources including Thomson Financial, Dataquest, and Moody's. Our data on licensing contain information on each individual contract. Details encompass the time the licensing contract was signed, the firms involved and a synopsis indicating the purpose, technology and the type of licensing, e.g. whether firms signed ex ante or ex post licensing contracts. For consistency with our theoretical model our empirical analysis of licensing is restricted to horizontal technology licensing. Hence, we have excluded vertical partnerships, such as those between semiconductor firms and computer, microelectronic or multimedia firms. In line with the previous literature we classified a licensing contract as horizontal if more than 50% of the firms had sales in the semiconductor industry. We also excluded contracts that were based exclusively on production and marketing licensing. Finally, we dropped another 22 licensing contracts which were related to litigation. This left us with 847 contracts over the whole time span.

We went through every synopsis and classified the licensing contracts into ex ante and ex post contracts. Ex ante licensing contracts are those contracts which provide patents on a specific technology to other firms before the technology has been explored. Ex post licensing contracts are those agreements which grant the right to another firm to use an already existing technology. The existing technology could be used either for manufacturing purposes, or to further develop an existing technology. Examples for ex ante and ex post licensing contracts are shown further below. We categorized contracts into 549 ex ante licensing contracts and 298 ex post licensing contracts.

Note that in more than 98% of the cases we were able to be unambiguously assign ex ante or ex post licensing contracts on the basis of the synopses. In only 2% of the cases contracts could have been categorized both in ex ante and ex post licensing contracts. In these cases firms exchanged technologies in order to jointly continue developing new technology. Since firms made the decision, before the new technology was developed we classified them as ex ante licensing contracts, to be consistent with our theoretical model.

Note also that the number of licensing contracts we observe is in line with that reported by Rowley et al. (2000) for an overlapping sample period. Their data derives from different data sources than ours.[21] The correspondence in the number of contracts observed confirms that our data set contains a comprehensive record of information on licensing available in the public domain. As Anand and Khanna (2000) note there is no requirement for firms to publish information on licensing contracts. Therefore, it is conceivable that some bias due to sample selection remains. However we are unaware of reasons for which firms should selectively favor ex ante or ex post licensing contracts when announcing licensing contracts to the public.

C.2 Patents

In order to capture firms' positions in technology space we use information on granted patents.[22] We use U.S. domestic patents in our study because the U.S. is the world's largest technology marketplace and it has become routine for non-U.S.-based firms to patent in the U.S. [Albert et al. (1991)]. Our data on granted patents are taken from the NBER patent data set established by Hall, Jaffe, and Trajtenberg (2001).[23] The database comprises detailed information on 3 million U.S. patents granted between 1963 and 1999, and all citations made between 1975 and 1999 (more than 16 million).

A major challenge in any study that examines the patenting activities of firms over time is to identify which patents are assigned to individual firms in a given year. Firms may patent under a variety of different firm names over time. To retrieve patent portfolios of the firms we follow the same procedure as Hall and Ziedonis (2001). This procedure was also used for our licensing data.

Using the patent database we extract detailed patent information for every semiconductor firm for our sample period 1989-1999. We use the number of annual granted patents, patent stocks (accumulated patents) dating back to 1963, as well as patent citations dating back to 1975. Moreover, in order to establish firms' position in technology space at a disaggregated level, we make use of information about the technology area that the filed invention belongs to. The USPTO has developed a highly elaborate classification system for the technologies to which the patented inventions belong consisting of about 400 main 3-digit patent classes. Each patent is assigned to an original classification. We chose 9 out of the 400 patent classes

[21] Rowley et al. (2000) study strategic alliances whereas we study licensing contracts. Our definition of a licensing contract is any contract that also includes an agreement to license technology. Therefore, both studies focus on a similar set of agreements between firms.

[22] By filing a patent an inventor discloses to the public a novel, useful, and non obvious invention. If the patent gets granted, the inventor receives the right to exclude others from using that patented invention for a certain time period, which is 20 years in the U.S.

[23] Further information about the database can be found at http://www.nber.org/patents/.

that are connected to memory chips, microcomponents and other semiconductor devices.

As the patent database lasts only until 1999 we need to take truncation of the data into account. Therefore, our patent based variables are based on annual patent shares. Throughout we divide the number of firms' patents and citations by the total number of patents and citations of all semiconductor firms in a given year.

C.3 Market data

Annual semiconductor market data at the firm-level were provided by Gartner Group. All merchant firms were tracked whose annual sales exceed \$10 million a year. Thus, we cover approximately the whole population of semiconductor firms and do not need to rely on business sheet information to infer market shares. On average, there are 155 companies present in the market every year. Approximately 60% of the firms had their headquarters in the U.S., whereas the rest were located in Japan, Europe, and other Asian countries. Again, we correct for mergers and acquisitions that were announced in the above mentioned sources.

We are able to separate the semiconductor market share into three different market segments: memory chips, microcomponents, and other devices. Based on this classification we are able to distinguish whether firms produce substitute or complementary products. If two firms have positive market shares in the same segment at least once, we consider them to be producing substitute products, and complementary products otherwise.

D Examples for ex ante and ex post licensing

This section contains examples of licensing contracts taken from our data set.

EX ANTE LICENSING

- Texas Instruments and NEC Corp entered into a ten-year cross-licensing agreement to patent semiconductors. Under the terms of the agreement, the two companies were to have use of each others patents involved in manufacturing semiconductors. Date: $06/12/1997$.
- Sony Corp and Oki Electric Industry Corp entered into an agreement to jointly develop a 0.25 micron semiconductor manufacturing process. Under the terms of the agreement, Oki was to use the technology for 256 Mbit "Dynamic Random Access Memory", while Sony was to produce logic integrated circuits (IC's) for home electronics and AV equipment. Financial terms were not disclosed. Date: $20/11/1995$.

EX POST LICENSING

- Ramtron International Corp, a unit of Ramtron Holdings Ltd, and International Business Machines Corp(IBM) signed a manufacturing and licensing agreement in which Ramtron was to grant IBM the rights to manufacture and market the Ramtron EDRAM dynamic random access memory chip. Under the terms of the agreement, IBM was to supply Ramtron with EDRAM chips. The EDRAM chips were to be manufactured at IBM's facility in Essex Junction, VT. No financial details were disclosed. Date: 05/08/1995.
- Compaq Computer Corp and Cyrix Corp entered into an agreement which stated that Cyrix Corp granted Compaq Computer a license to manufacture Cyrix Corp's M1 microprocessor chips. The agreement stated that production of the M1 microprocessor chips in the first quarter of 1995. Financial terms of the agreement were not disclosed. Date: 05/10/1994.