# Are Licensing Agreements Appropriate Instruments to Cut Through the Patent Thicket?

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## Abstract

We study whether licensing agreements can help firms to cut through the patent thicket and to prevent hold-up problems. Using a data set covering the semiconductor industry between 1989 and 1999, descriptive results reveal a puzzling picture: while the number of patents more than doubled over the time period, the number of licensing agreements followed an inverse U-shape. This relationship is surprising given the fact that licensing agreements are supposed to resolve the hold-up problem. A more detailed analysis and the distinction between ex ante and ex post licensing contracts give the following results: the degree to which firms block each other in the technology space explains firms' licensing choices. Ex ante licensing agreements represent useful instruments for firms to avoid getting into patent races if the degree of blocking is expected to be high. The type of contracts also allows firms to avoid high investments in Research and Development. Ex post licensing agreements are more important for firm pairs which mistakenly expect blocking to matter little, and which are characterized by larger and more similar market shares. Worryingly, our empirical results show that firms' tendency to engage in licensing deals decreases as property rights become more fragmented. Moreover, ex ante licensing agreements are characterized by significant transaction and contracting costs which diminish with experience.

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

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# 1 Introduction

Over the last two decades, technology in high tech industries has become increasingly complex and modular. The complexity of technology requires firms to patent multiple inventions protected by multiple patents. Modularity implies that final products depend on many component inventions. When patents on final products belong to multiple firms bargaining delays and hold-up are likely (Shapiro, 2001). To improve bargaining positions firms regularly engage in "patent portfolio races" contributing to explosive growth of patenting (Hall and Ziedonis, 2001).[1]

A challenging implication of the patenting growth is the associated emergence of patent thickets - sets of overlapping patents with uncertain validity and scope (Heller and Eisenberg, 1998; Shapiro, 2001; Hall and Ziedonis, 2001; Ziedonis, 2004; von Graevenitz et al., 2008a, 2011). Patent thickets incorporate the danger that firms face a hold-up problem, if a (blocking) patent which is necessary for a firm to adopt a new technology is granted to a different firm. Blocking patents are a serious concern for firms and policy makers as they might prevent firms from inventing a new technology, causing a hold-up problem (Shapiro, 2001).

Recent policy debates address the question whether patent thickets undermine the proper functioning of patent systems and raise costs to innovate. It is also claimed that patent thickets may frequently inhibit innovative activity rather than fostering it due to the hold-up problem (Jaffe and Lerner, 2004; Bessen and Meurer, 2008).[2]

It is frequently argued that licensing agreements represent appropriate instruments for firms to cut through the patent thicket and to resolve the hold-up problem (Grindley and Teece, 1997; Clark and Konrad, 2008). Licensing agreements allow firms to exchange patents and guarantee each other "freedom to operate" (Grindley and Teece, 1997). A prominent example is Texas Instruments which pursued an aggressive litigation and licensing strategy more than twenty years ago. However, a first look at our data set on the semiconductor industry provides a rather puzzling picture on the relationship between patents and licensing agreements. While the number of patents steadily increased and more than doubled from 1989 until 1999, the number of licensing contracts follows an inverse U-shape over time. In contrast, we would expect a positive relationship between the numbers of licensing agreements and patents if licensing is purely an instrument to resolve the hold-up problem.

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[1] Other reasons which may have caused the growth in patenting are legal reforms (Jaffe, 2000) and feedback mechanisms within the patent system (Ziedonis, 2004).

[2] Patent overlap is due to the widely documented difficulty of patent offices to reject weak patents (Lemley, 2001; Federal Trade Commission, 2003; Lei and Wright, 2009). Patent thickets imply the risk for patent offices to grant overlapping patent rights that are susceptible to be challenged in court. Industries that are increasingly affected by patent thickets (Huys et al., 2009) are the semiconductor-, information-, and biotechnology industry (Hall and Ziedonis, 2001; Ziedonis, 2004). Patent thickets are also prevalent in medical areas such as genetic diagnostic testing.

The aim of this paper is to examine whether licensing contracts are appropriate instruments to mitigate the hold-up problem. The study is primarily empirical and investigates why firms sign different types of licensing agreements and analyzes their effects on investments in Research and Development. Up until now, few empirical studies have focused on licensing agreements (Anand and Khanna, 2000; Galasso, 2007). These focus on ex post licensing agreements which grant firms the right to use another firm's existing patented inventions. The agreements are formed after the invention has been completed. In contrast ex ante licensing contracts, which we also study, grant firms the right to use another firm's emerging patents. They are signed before the invention has been patented.[3] Interestingly, ex ante licensing contracts are more frequently signed between firms than ex post licensing contracts. It is therefore surprising, that most previous empirical studies focus on ex post licensing, while ex ante licensing has hardly received attention in the literature (Grindley and Teece, 1997).

Our study builds on a simple theoretical model, in which firms initially have the choice to license ex ante, or to start a patent portfolio race. If they do not license ex ante, they choose at the end of the race to license ex post, or not to license at all. The theoretical model provides hypotheses with respect to firms' licensing choices and the corresponding investments in Research and Development. It also enables us to specify an empirical model and to develop an identification strategy in our empirical model. We use firm-level licensing, product market and patent data on the semiconductor industry from 1989 until 1999. Accounting for the fact that firms self-select themselves into ex ante and ex post licensing agreements, we estimate a bivariate probit selection and an endogenous switching model.

We find that firms make their licensing decisions based on their technological relationships, i.e., their expected and realized levels of blocking. We provide evidence that ex post licensing contracts are used as an instrument to resolve hold-up. It is interesting to note, that under ex post licensing, firms engage in costly patent portfolio races and drastically increase their investment in Research and Development (R&D) or patenting levels. Firms build up patent portfolios and collect additional (blocking) patents to strengthen their bargaining positions (Grindley and Teece, 1997; Lemley, 2001). This finding is in line with (Hall and Ziedonis, 2001; Ziedonis, 2004) who claim that firms' bargaining positions in disputes over patent validity or negotiations are determined by the size of firms' patent portfolios. Moreover, we find that firms sign ex ante licensing contracts to avoid hold-up. In ex ante licensing, firms are able to reduce the pace of patent races and lower their patenting efforts. Consequently, ex ante licensing can be used as a tool to avoid to drastically increase R&D investments or the degree of patenting. It is interesting to note, that firms' decisions to

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[3] Examples of ex ante and ex post licensing contracts are shown in Appendix C.1. We also provide a detailed discussion and descriptive statistics on both types of licensing in the next section.

choose a specific type of licensing are not driven by cost sharing arguments which is a common explanation in models of R&D cooperation, see e.g., Röller et al. (2007). We also find that ex ante licensing allows less innovative firms to insure themselves against hold-up. Importantly, legal and organizational expertise represent high initial transaction or contracting costs which only applies to ex ante licensing agreements, but not to ex post licensing contracts. Our results also show that both types of licensing are important for firms with larger and more similar production facilities. They heavily rely on licensing to insure the returns from large scale production. An increased degree of fragmentation of patent ownership constitutes an impediment to engage in licensing deals. It reduces the incidence of licensing, which confirms the argument made by Ziedonis (2004).

Measuring the level of blocking using patent data is challenging. We rely primarily on a synthetic measure of blocking obtained from U.S. patent data. As this measure may be interpreted in alternative ways we perform a robustness check for this variable using European patent data which contains a direct measure of blocking. We are able to confirm our findings with this measure.

The remainder of the paper is organized as follows: in Section 2 we describe licensing trends in the semiconductor industry. Section 3 presents our hypotheses and our empirical model. Afterwards, we discuss the data in Section 4 and Section 5 describes our empirical results. Finally, Section 6 concludes.

## 2 Licensing in the Semiconductor Industry

In this section, we describe firms' licensing behavior in the semiconductor industry. In an empirical study on 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 with respect to entry, exit and patenting in the semiconductor industry. Additionally, we investigate if the degree of blocking of firms' patent portfolios or fragmentation of patent portfolios are related to firms' licensing behavior.

To study licensing we have constructed a data set comprised of 847 licensing contracts between 268 firms covering the period from 1989 until 1999. 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.[4]

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[4] More information on the data sources and how the dataset was constructed is provided in Chapter 4 and in Appendix C.

Figure 1a

Growth of revenues and firm numbers in the semiconductor industry

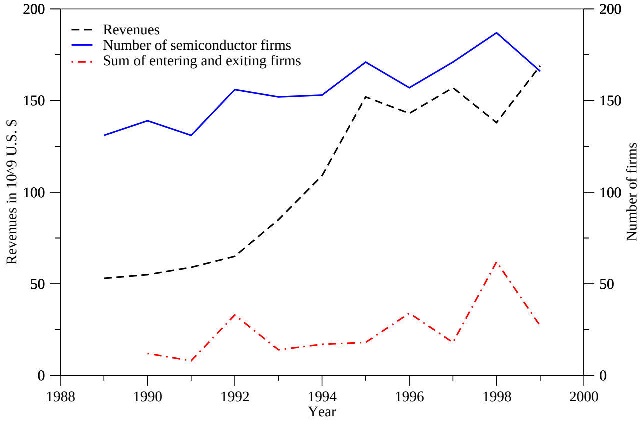

Figure 1b

Licensing and patenting activity in the semiconductor industry

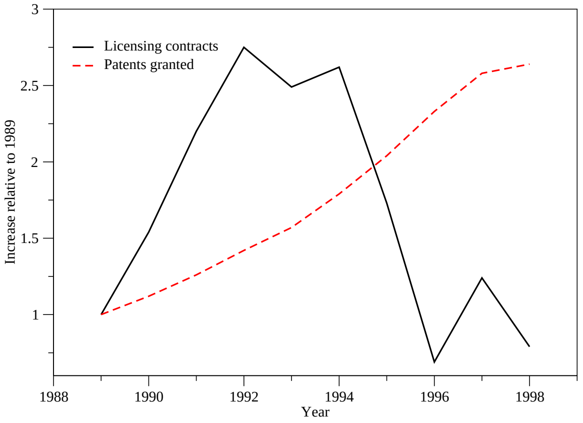

Figure 1a shows that total revenues in the semiconductor industry grow substantially over the period of our sample. This fact is accompanied with a significant increase in the number of active semiconductor firms. However, the figure also demonstrates that the growth process in industry revenues diminishes after 1996. The long run trend in the number of firms in the market increases steadily throughout the entire period.

The semiconductor industry also experienced a strong surge in patenting activity after 1985 (Hall and Ziedonis, 2001; Ziedonis, 2003, 2004). Figure 1b displays 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. Hall and Ziedonis (2001) argue that this development is due to strategic patenting in the face of an emerging patent thicket. The number of licensing contracts rather follows an inverse U-shape of time. This is surprising because we might expect there to be a greater demand for licensing as the number of patents grows.[5]

Figure 2a below shows the average number of licensing contracts per firm in the semiconductor industry. The figure displays a hump shape similar to the absolute number of licensing contracts. This rules out the explanation that the smaller number of licenses at the end of the 90's could be due to fewer semiconductor firms being active in the market. Between 1991 and 1994, the number of licensing contracts per firms was rather constant. The decline in licensing activity persists after 1994.[6]

Next, we deepen our insights on licensing and distinguish between ex ante and ex post licensing. As mentioned above, ex ante licensing contracts commit firms to provide a certain technology (or patents) to

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[5] 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.

[6] Vonortas (2003) investigates 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

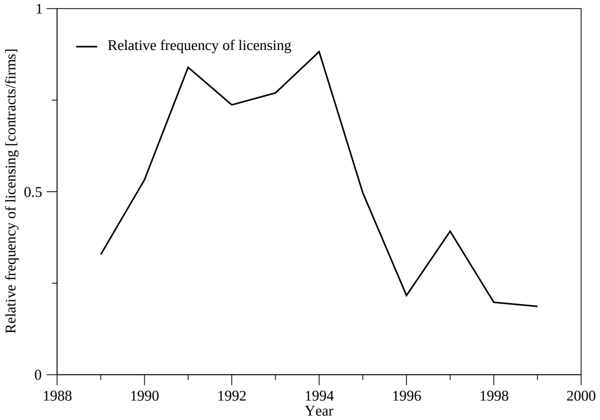
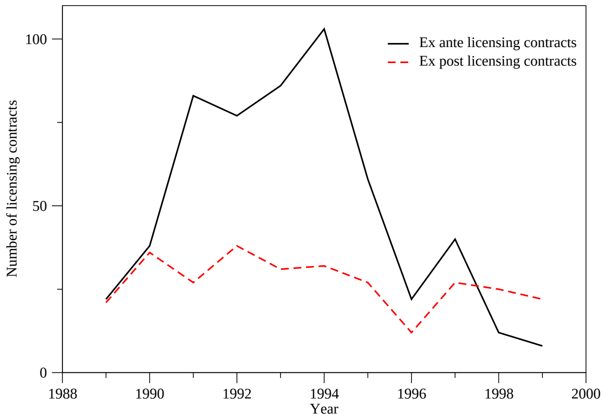


Figure 2b

Total ex ante and ex post licensing contracts in the semiconductor industry



other firms before the technology has been explored. Ex post contracts cover cases in which firms grant rights to other firms for already existing technologies (or patents).[7]

Figure 2b shows that ex ante licensing is far more volatile over time 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). To summarize, Figures 2a and 2b show clearly that, over the period of our sample, the inverse U-shape of licensing is predominantly a result of the evolution of ex ante licensing agreements.

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.[8] Previous studies, see e.g., Grindley and Teece (1997) and Shapiro (2001, 2003), primarily 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 in both, ex ante and ex post licensing.

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[7] For more information on the data sources and examples of licensing contracts, see Appendix C.

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

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 further information on ex ante and ex post licensing agreements. The table shows that the average firm was engaged in approximately 6 contracts between 1989 and 1999. On average, a 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.

Interestingly, the table indicates no significant differences between ex ante and ex post licensing contracts. This observation is partly due to the fact that some firms use both types of licensing contracts as shown in Table 1.

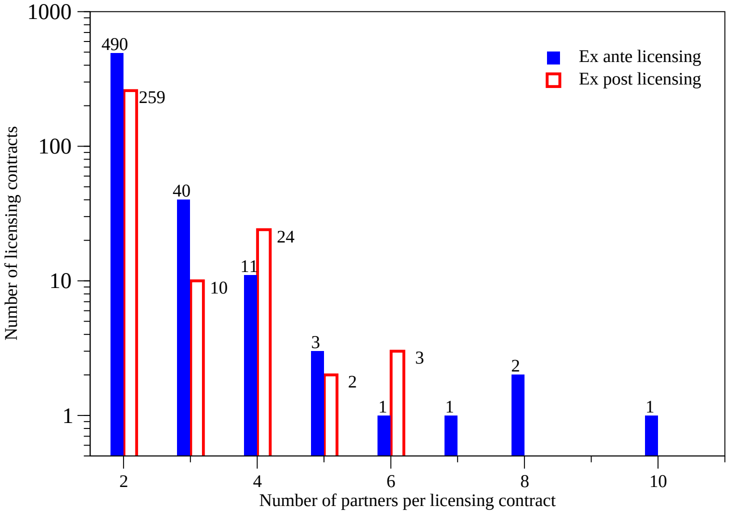
Table 2: Sample Statistics for Firms by Licensing Contract Type

| | 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 between 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



To summarize, the comparison between ex ante and ex post licensing suggests that the observed trends are not the result of greater licensing activity by a small group of firms specializing in ex ante licensing. Consequently, we expect underlying changes in the industry overall, i.e., the product and technology market, to drive firms' decisions to license ex ante or ex post. Therefore, it is important to account for all firms in the industry and to capture the evolution of the industry in order to gain further insights into analyzing the decision to license ex ante or ex post, or not to license at all. Furthermore, an aggregate measure of the strength of the patent thicket, i.e., using patent counts, is not an appropriate measure to explain firms' licensing choices. This measure performs rather poorly to explain firms' incentives to engage into licensing overall; neither does it explain firms' choices between ex ante and ex post licensing. In order to better reflect the patent thicket, we continue to focus on measures that explicitly account for firms' relationships in the technology space and capture the extent to which firms might block each other in the technology space. In constructing the blocking measures and measuring firms' relatedness in technology space, we change our focus from individual firms to firm pairs.

The construction of the blocking measure builds on the uncentered correlation coefficient, suggested by Jaffe (1986). It is based on firm-pairs and interacts a measure of firms' technological proximity with a measure of their cross citations. The blocking measure is high, if firms patent in similar technology classes and cite each other frequently within the same technology classes.[9] Figure 4a reveals that blocking initially increased and then decreased over the sample period. Overall, Figure 4a indicates that the blocking variable might be an appropriate measure to explain the licensing trends discussed previously.

Figure 4a

Blocking in firm pairs

Figure 4b

Fragmentation in pairs

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 for hold-up. If licensing contracts resolve such potential we might expect licensing to be correlated with fragmentation. Figure 4b presents the evolution of fragmentation of technology ownership over time based on the citations from

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[9] For a more precise definition of this measure we refer to Section 4.

the patents held by a firm pair.[10] Interestingly, Figure 4b does not initially reveal an obvious relationship. We return to this point when we discuss the estimation results in Section 5.

Next, we derive our hypotheses regarding firms' strategies of forming ex ante and ex post licensing agreements. Afterwards, we discuss our empirical model.

## 3 Licensing and Patenting in the Patent Thicket

We study two solutions to the problem of blocking in patent thickets: ex ante and ex post licensing. Ex ante licensing contracts prevent hold-up for a specific period. They cover patents that arrive in that period. Firms that do not license ex ante keep open the option to license ex post or not to license. Ex post contracts resolve hold-up given firms' existing patents. In the following, we introduce our hypotheses which are derived from the theoretical model, shown in Appendix B.

### 3.1 A Summary of our Theoretical Model

The theoretical model explains how firms' decisions to engage in ex ante or ex post licensing depend on the degree of blocking. We consider two firms being involved in a patent race. Every firm's goal is to invent a new technology.[11] Each technology requires firms to invent multiple inventions and each invention will be protected by a patent. Hence, firms are engaged in a patent race targeting an entire portfolio of patents. Since firms race for their patents simultaneously, some of their patents might block the opponent from inventing the new technology depending on the degree of relatedness of their technologies. The more similar the technologies, the more likely it is that a patent is held by a different firm, representing a blocking patent. Blocking patents cause a hold-up problem as they hamper the opponent from successfully inventing the new technology.

Firms have the option to exchange blocking patents by signing licensing agreements. Figure 5 below presents the sequence of firms' licensing decisions. As the figure illustrates, at stage 1 firms decide whether to license ex ante, or not. This decision will be made depending on what firms expect the degree of realized blocking to be after the patent race, i.e., in stage 3. If they sign an ex ante licensing agreement, they commit to exchange all future patents. If firms did not sign an ex ante licensing contract in stage 1, they enter a patent race in stage 2 and invest in R&D. After the race (stage 3), they have the option to sign an ex post licensing contract or not to license at all. This decision will be made depending on how the realized degree

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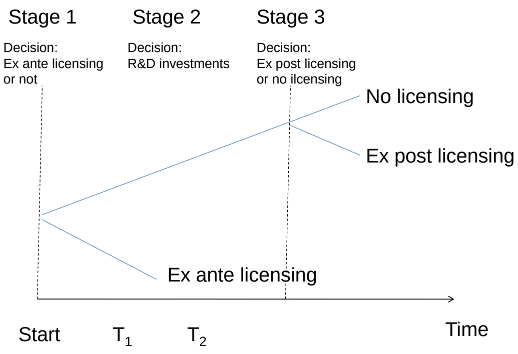
[10] See Section 5 for further information on the variable definition.

[11] Note that the technologies every firm is racing for might be related.

of blocking turns out to be at the end of the race.

Figure 5: Timing of Licensing Decisions



In case of ex post licensing, firms agree to exchange their blocking patents at the end of the patent portfolio race. The exchange of blocking patents will be determined by firms' bargaining power which is dependent on their patent portfolios.

Our theoretical model in Appendix B shows that firms' value functions of ex post and ex ante licensing depend on the degree of expected and realized blocking, see Appendix B, equations (13) and (25), respectively. The value of ex post licensing declines if the degree of realized blocking increases, see Appendix B, Propositions (2) and (3). In contrast, the value of ex ante licensing is not affected by the realized degree of blocking, but depends on the expected degree of blocking.

Our model emphasizes that the decision between ex ante and ex post licensing is not only dependent on the degree of blocking, but also a matter of (fixed) transaction costs which firms have to incur when getting engaged into licensing deals. Those costs need to be incurred because firms have to devote time and resources in designing licensing contracts.[12] Applying a transaction cost argument, we predict firms' choices between different licensing agreements and expected and realized blocking. We derive the following hypotheses from our theory:

### Hypothesis 1

*Firms license ex ante, if expected blocking is high.*

If expected blocking is high firms engage in ex ante licensing and avoid to drastically increase their investments in R&D, see Appendix B, Proposition (3). Firms drastically increase their R&D investments in order to collect as many patents as possible and to build up their patent portfolios. Higher patent portfolios

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[12] Without transaction costs, our model would predict that firms always prefer ex ante licensing.

will strengthen firms' bargaining positions in case they had to form ex post licensing agreement at the end of the race. Therefore, ex ante licensing is used as an instrument to prevent a patent portfolio race and to avoid overinvesting in R&D which diminishes the value of the technology.

**Hypothesis 2**

*Firms license ex post, if expected blocking is low and realized blocking is high.*

If firms signed an ex ante contract, instead, they had to pay transaction costs at the beginning of the game with certainty. At the beginning of the game, however, it still is uncertain what the realized degree of blocking will turn out to be in stage 3. In case the realized degree of blocking turns out to be low, no ex post licensing contract would have been necessary and no transaction costs had to be incurred. Hence, if realized blocking turns out to be low, firms will not have to license at all, and they save their transaction costs. Consequently, if expected blocking is low, firms are better off not to license ex ante and wait for the outcome of the realized degree of blocking at the end of the race. If the realized blocking eventually turns out to be high, firms will still have the option to sign an ex post licensing contract and pay the transaction costs. If realized blocking is low, firms do not license at all and they save their transaction costs.

Our theoretical model in Appendix B and the arguments above show that the decision between ex ante and ex post licensing is not only dependent on the degree of blocking, but also a matter of transaction costs, i.e., the costs of forming licensing contracts. Therefore, our next hypotheses explicitly account for the importance of transaction costs in forming licensing agreements. Since transaction costs incorporate explicit as well as implicit costs and neither of those costs are included in our dataset, we make the assumption that the transaction costs will decrease with the experience a firm has of a particular form of licensing. Since lower transaction costs increase the incentive to forming a specific licensing agreement, we derive the following hypotheses:

**Hypothesis 3**

*The probability of observing ex ante licensing increases in firms' experience with ex ante licensing.*

and

**Hypothesis 4**

*The probability of observing ex post licensing increases in firms' experience with ex post licensing.*

Finally, our theoretical model provides results about firms' incentives to invest in R&D under ex ante and ex post licensing. Our Proposition 3 in Appendix B shows that increases in blocking have the effect of raising firms' R&D investments in ex post licensing. This results from the fact that firms try to increase their patent portfolios and collect more patents to strengthen their bargaining position for a possible ex post licensing deal in the future. In contrast, R&D incentives under ex ante licensing are independent of the realized degree of blocking. Hence, firms invest less in R&D and produce fewer patents.

**Hypothesis 5**

*Firms produce fewer patents under ex ante licensing.*

In the following section, we introduce the empirical model which focuses on testing Hypotheses 1 to 4.

### 3.2 The Empirical Framework

This section introduces the empirical model, i.e. the decision to license ex ante and ex post, to test our hypotheses.

**The Ex Ante Licensing Decision** Firms license ex ante if the value is expected to be higher than the value under ex post licensing or not to license at all. Hence, the selection equation of our empirical model can be written as follows:

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

where $V_a$, $V_p$ and $V_n$ are the values corresponding to ex ante, ex post and no licensing, respectively. Note, that the values of ex post licensing and no licensing depend on the expected degree of blocking ($\beta$).[13] $T_a$ and $T_p$ are transaction costs associated with ex ante and ex post licensing. $\Phi$ is the cumulative density function and $\epsilon$ captures random variation in licensing and is assumed to be normally distributed.

It is important to note that the net values for ex ante and ex post licensing also depend on other factors, beyond the degrees of blocking and the transaction costs. Those factors describe firms' patent stocks and their product market characteristics. For the sake of tractability they do not enter our theoretical model. Nevertheless, they are important determinants of firms' licensing choices. We therefore include them in our model as control variables.

The resulting empirical specification for the selection equation of our model is:[14]

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

where $EB$ is our measure of the expected blocking in a firm pair, $\boldsymbol{PM}$ is a vector of measures reflecting

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[13] Remember, that the expected values of ex post licensing ($V_p$) and not licensing ($V_n$) are decreasing functions of the expected degree of blocking ($\beta$).

[14] Note, that all variables are constructed on the basis of firm-pairs.

firms' product market characteristics, $\boldsymbol{PS}$ is a vector of measures capturing the size of firms' patent stocks. Since we do not observe transaction costs associated with ex ante and ex post licensing, we proxy them using firms' experience in ex ante and ex post licensing, measured by $L_A$ and $L_P$, respectively. $L_A, L_P$ count the number of previous ex ante and ex post contracts the firms were involved in. The error term $\epsilon$ captures random components of the expected value of ex ante licensing. The term is assumed to have a variance of unity and is normally distributed.

Hypothesis 1 predicts the sign of blocking $\beta_a^{EB} > 0$, i.e., greater expected blocking increases the probability to form an ex ante licensing agreement. Moreover, Hypothesis 3 predicts the sign of $\beta_a^{LA} > 0$ and $\beta_a^{LP} < 0$.

**The Ex Post Licensing Decision** If the firms decided not to form an ex ante licensing agreement in stage 1, they choose in stage 3, whether to engage in an ex post licensing deal, or not to license at all. At this stage, the degree of realized blocking has dissipated, see Figure 5.

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 $\eta$ captures random components of the expected value of not licensing and licensing ex post. It is normally distributed with a variance of unity. 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, see Appendix B, equation (12). Remember, from Proposition 5 that the difference $v_w + v_l - V_n$ is zero if there is no blocking and it is increasing in the degree of blocking.

The resulting specification of our empirical model is:[15]

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

where $B$ measures the realization of blocking. In case that realized blocking is sufficiently high, Hypothesis 2 predicts that firms will sign an ex post licensing contract to resolve blocking: $\beta_p^B > 0$. Moreover, according to Hypothesis 4, we expect a positive relationship between ex post licensing and firms' experience of past ex post licensing contracts, i.e., $\beta_p^{LP} > 0$. In line with ex ante licensing and similar to equation (2), we

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[15] Variables are again defined in firm-pairs.

control for firms' product market characteristics and their patent stocks.

## 4 Definition of Variables and Descriptive Statistics

In this section, we introduce the variable definitions and provide further descriptive statistics. Afterwards, we introduce the econometric specification, i.e., the bivariate probit selection model.

As mentioned in Section 2, the data are originated from three different data sources: licensing data are provided by Thompson Financial, product market data are provided by Gartner and the patent data were taken from the NBER database.[16]

Our data set covers the period 1989 until 1999. The variables are defined in firm-pairs and on an annual basis. The year in which a licensing contract is signed is also the reference year for which our variables are generated. For the sake of notational convenience we drop the subscript that refers to the time period $t$.

**Dependent Variables -** $\Pi_a, \Pi_p, A$

$\Pi_a$ and $\Pi_b$ indicate whether a firm pair entered into an ex ante or an ex post licensing contract, respectively. The variable $A$ 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 in period $t$ depends on the realized (or contemporaneous) degree of blocking $B$ in period $t$.

Blocking of one firm's activities by the other is more likely, if two more technologically similar firms cite each others' patents more often. Hence, this variable encompasses two dimensions, the technological overlap 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 our blocking variable as the interaction of these measures.

Technological similarity is measured as the uncentered correlation coefficient[17] of the two firms' patent applications in a given year across nine patent classes, to which all semiconductor patents may be assigned.[18] The definition of this measure is:

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

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[16] Data sources are described in detail in Appendix C.

[17] The measure is widely used to capture technological proximity in the literature on patents, see e.g., (Jaffe, 1986).

[18] 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).

where $A^{lc}$ is the number of patent applications by firm $l \in \{i, j\}$ in patent class $c$.

Citation intensity is measured as the share of the number of citations that firm $i$'s patents cite firm $j$'s patents, divided by the total number of firm $i$'s citations:

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

where $c^{ij}$ ($c^{ik}$) is the number of citations of firm $j$ (firm $k$) by firm $i$, and $k \in K$ is the total number of $K$ firms present in the industry.

Finally, blocking is defined as:

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

Table 3 below shows descriptive statistics on the blocking measure. The measure of blocking is highest on average when firms engaged in ex post licensing and lowest on average when they did not license at all.

It is important to mention that we have no direct information in the U.S. patent data of litigation or of cease and desist letters which would capture the degree of blocking and how serious the threat of hold-up turns out to be. However, further below we thoroughly test for the appropriateness of our definition of blocking using additional information from European patents.

**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 use a proxy approach, which builds on the assumption that the time lags between firms' decisions to license ex ante and ex post is one year, see Figure 5. To clarify the timing structure consider an example in which firms decide whether to license ex ante in period $t$: firms are at the start of the time path in Figure 5. Suppose firms decided not to form an ex ante licensing contract in period $t$. Then, they decide in period $t + 1$ whether to form an ex post licensing deal or not to license at all, based on the realized degree of blocking in period $t + 1$. Hence, the expectation of realized blocking for period $t + 1$ is formed on the basis of the contemporaneous realized degree of blocking in period $t$. Moreover, if we observe an ex post or no licensing agreement in period $t + 1$, we can infer that firms decided in period $t$ not to engage in ex ante licensing agreement.[19]

Table 3 shows that the measure of realized degree of blocking ($B$) under ex post licensing (0.011) is higher than under no licensing (0.005). Moreover, the expected degree of blocking ($EB$) is higher in the ex ante licensing case (0.007) than in in the no licensing case (0.004).

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[19] We tested for longer time lags with regard to making the decision between ex ante and ex post licensing. Results are not significantly different. Expectations based on longer time lags have smaller marginal effects on firms' licensing choices, though.

### Robustness Check for the Blocking Measure

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. 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 also used by von Graevenitz et al. (2007) and von Graevenitz et al. (2008b) to identify patent thickets. Using this data, we generate a count on 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. Next, we identify the equivalent European semiconductor patents for the U.S. semiconductor patents in our data set and examine the correlation between our blocking measure and the blocking just described.[20] The correlation is always in the medium range ($> 0.3$) and significantly different from zero. Appendix A also provides the estimation results of our main empirical model using the alternative measures of blocking.

### Product Market Competition - $PM$

We also control for competition between firms in the product and the technology markets. The following variables do not appear in the theoretical model, but are used for further controls in the empirical model. We employ three measures to control for product market competition:

**Average Market Shares** We use the average market share of each firm pair in the semiconductor product market. 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.[21] 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 engage in licensing.

**Difference in Market Shares** This variable measures firm size asymmetries for each firm pair in the semiconductor industry. Differences in firm size may reduce the propensity of firms to enter into a licensing contract as size proxies the prestige of each firm in a pair (Stuart, 1998). Descriptive statistics in Table 3 show the difference in market shares is lowest for firm-pairs engaged in ex post licensing.

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[20] 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).

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

**Multimarket Participation** We control for the number of different product markets within the semiconductor industry in which firms are active. We distinguish between microcomponents, memory chips and other devices. Firms being active in several product markets are exposed to more competitors in technology space. The descriptive statistics in Table 3 indicate that firms engaged in licensing are more diversified than firms that are not engaged in licensing.

**Patent Stocks - $PS$**

We also control for firms' relative strength in technology markets and the degree of their fragmentation in these markets. We employ three patent stock measures:

**Average Patent Stocks** The size of firms' joint patent stocks is an indicator for firms' activity in the technology markets and might control for a higher tendency to getting involved in licensing deals. Table 3 reveals that licensing firms have larger patent stocks than non licensing firms.

**Difference in Patent Stocks** This measure controls for differences in the size of firms' patent stocks. As shown in Table 3 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 might hold-up a firm, she controls for the fragmentation of a firm's patent citation stock. We include the measure in our empirical model specification as firms' propensity to enter into licensing contracts could decrease if fragmentation increases. The reason is that the required patents needed by one firm to successfully invent a new technology are held by different firms. We use the patent citation stock between two firms at the period of time at which they make their licensing decision. We also apply the correction suggested in the appendix of Hall et al. (2005) to control for a bias resulting from low counts. Table 3 shows that fragmentation is on average greater for firm pairs that engage in licensing.[22]

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

As noted above, firms characterized by more experience in licensing might face lower transaction costs for subsequent contracts. We control for experience of ex ante and ex post licensing separately as these types of contracts are usually designed differently.

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

**The Sample** The inclusion of product market and patent data results in $250$ ex ante and $294$ ex post licensing contracts.[23] Descriptive information for all variables used in our regressions is presented in Table 3. We are able to use $36,275$ observations in our regressions.

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 | $\Pi_a$ | 1 | 0 | 0 | 0.007 | - | 0 | 1 |
| Ex post licensing | $\Pi_p$ | 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 | | | |

We now turn to our empirical models and discuss the results.

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[23] Note, Section 2 reports unconditional descriptive statistics on licensing agreements. Table 3 shows descriptives conditioning on the fact that we have non-missing values for the market shares. The number of licensing contracts further decreases to 212 ex ante and 261 ex post licensing contracts in our regressions due to having a complete set of observations for every firm and licensing contract.

## 5 Empirical Model and Identification

In this section, we focus on testing our Hypotheses 1 to 4 introduced in Section 3. In Section 5.2, we test our Hypothesis 5 and employ an endogenous switching model.

Remember, our Hypotheses 1 and 3 predict that higher expected blocking and greater experience of ex ante licensing increase the probability of observing ex ante licensing. Moreover, Hypotheses 2 and 4 predict that higher degrees of realized blocking and greater experience of ex post licensing increase the probability to engage in ex post licensing. To test these predictions, we estimate a bivariate probit selection model as introduced in equation (6).

### 5.1 Effects of Blocking and Transaction Costs on Firms' Licensing Choices

Building on equations 2 and 4 in Section 3.2, the model takes the following form:

$$\begin{aligned}
\Pi_a^* &= \alpha_a + \beta_a^{EB} EB + \boldsymbol{\beta}_a^{PM} \boldsymbol{PM} + \boldsymbol{\beta}_a^{PS} \boldsymbol{PS} + \beta^{LA} L_A + \beta^{LP} L_P + \epsilon \qquad (6)\\
\Pi_p^* &= \alpha_p + \beta_p^{B} B + \boldsymbol{\beta}_p^{PM} \boldsymbol{PM} + \boldsymbol{\beta}_p^{PS} \boldsymbol{PS} + \beta_p^{LP} L_P + \eta \\
\Pi_a &= \begin{cases} 1 & \text{if} \quad \Pi_a^* > 0 \\ 0 & \text{if} \quad \Pi_a^* \leq 0 \end{cases} \qquad \Pi_p = \begin{cases} 1 & \text{if} \quad \Pi_p^* > 0 \\ 0 & \text{if} \quad \Pi_p^* \leq 0 \end{cases}.
\end{aligned}$$

According to the terminology of bivariate probit selection models, as well as adapting the sequential decision process from our theoretical model, we also call the first equation (2), i.e., the decision to form an ex ante licensing contract, the selection equation. The second equation (4), i.e., the decision to engage in ex post licensing, is called the outcome equation. In order to ensure that the bivariate probit selection model is identified, we have to rely on exclusion restrictions for the ex post licensing or outcome equation. Based on our theoretical model, expected blocking is not supposed to enter the ex post licensing equation and may serve as an exclusion restriction (instrument) to identify our model. We throughly perform several tests to confirm the validity of this instrument. We estimate the equations of this model jointly by FIML. The results and several robustness checks are discussed in the next section.

**Identification and Estimation Results** Table (4) shows the results of 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 or ex post licensing equation, see column (1). Columns (3) and (4) report the same model, but expected blocking is used as an instrument and therefore removed from the outcome equation.

Evidence of sample selection is present in both models as the correlation coefficient $\rho$ is significant and negative. The 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 due to a low expected degree of blocking, will raise the likelihood to license ex post given they face a high degree of realized blocking. Note also that the correlation coefficient is significantly different from one.

Table 4: Coefficients for Bivariate Probit Selection Models of Licensing

| | Bivariate Probit | | Bivariate Probit | |
|---|---|---|---|---|
| Independent Variable | Pr (Ex post) (1) | Pr (Ex ante) (2) | Pr (Ex post) (3) | Pr (Ex ante) (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 | | -5.0·e-05** | | -2.0·e-04** |
| | | (9.0e-05) | | (1.0e-05) |
| 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) |
| $\rho$ | -0.976*** | | -0.975*** | |
| | (0.018) | | (0.02) | |
| $-\ln L$ | 2,613.175 | | -2,613.799 | |

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

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

Comparing the two alternative specifications, i.e., columns (1) and (2) with columns (3) and (4), it turns out that the expected blocking ($EB$) in column (1) is not significant in the outcome equation of the sample selection model. This result is consistent with our theory, as ex post licensing is supposed to be independent of expected blocking. This result also confirms the validity of our exclusion restriction derived from theory, i.e., expected blocking is excluded from the outcome equation. Moreover, a likelihood ratio test comparing the two bivariate probit models reveals that expected blocking is a valid exclusion restriction ($\chi^2(1) = 1.25$). In the following, we focus on describing the results shown in columns (3) and (4).

With respect to Hypotheses 1 and 2, we find that a higher degree of expected blocking increases the probability of ex ante licensing and higher realized blocking increases the likelihood of getting engaged in ex post licensing. Similarly, higher realizations of blocking raise the probability of observing ex post licensing. The estimated coefficients are highly significant. These findings show that expected and realized blocking determines firms' licensing choices which also provides support for our theoretical patent portfolio race model. Hence, we can confirm both hypotheses.

How important are the blocking measures in determining firms' licensing choices? The conditional probability of observing ex ante licensing based on our preferred model is $0.0054$. The conditional probability of ex post licensing is $0.0071$.[24] 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. The probability of observing ex post licensing rises by $(54\%)$ if blocking increases by one standard deviation at the mean. These results confirm the relevance of expected and realized blocking in determining firms' licensing choices. Moreover, our results also emphasize the appropriateness of our theoretical model, i.e., firms use licensing contracts to exchange blocking patents and to overcome the hold-up problem.

As noted above, we thoroughly tested for the robustness of our blocking measure. We constructed an alternative measure of blocking, which is based on a direct indicator of blocking between patents contained in European patent data. The estimation results are shown in Appendix A. According to the results, we cannot reject our Hypotheses 1 and 2. This gives us additional confidence in the robustness of our estimation results.

We now turn to our Hypotheses 3 and 4, which focus on the relevance of transaction costs in firms' licensing decisions. Hypothesis 3 states that experience with ex ante (ex post) licensing will increase (reduce)

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[24] These low probabilities result from the large number of firm pairs in the semiconductor industry which do not license.

the probability of ex ante licensing. Coefficients on these variables are highly significant in the selection equation, see column (4). 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 $5\%$. Hence, we can confirm Hypothesis 3: more experience of ex ante (ex post) licensing increases (decreases) the probability of ex ante licensing. Regarding Hypothesis 4, 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 $(ii)$ we include both previous ex post and ex ante licensing in the outcome equation ($\chi^2(1) = -5.73$). We can clearly reject these alternative specifications. Therefore, Hypothesis 4 is not confirmed in our data set: transaction costs of licensing ex post are insignificant in the ex post licensing decision.

Results reported in Table 4 show that most variables which control for firms' importance in semiconductor product and technology markets are highly significant and have a substantial impact in determining ex ante and ex post licensing. Larger firm pairs in the product market are more likely to license ex ante. A one standard deviation increase in market shares of a firm pair raises the probability of observing ex ante licensing by $20\%$. An increase in market shares by one standard deviation raises the probability of ex post licensing by $43\%$. Hence, ex post licensing agreements are more important for firms characterized by larger market shares: firms with important production facilities rely on ex post licensing to guarantee "freedom to operate" (Grindley and Teece, 1997). Their returns are highly dependent on the ability to resolve blocking and to cut through the patent thicket.

Firms characterized by more similar market shares also have a higher incentive to engage into licensing. A one standard deviation increase in the symmetry of market shares increases the probability of observing ex ante licensing by $19\%$ and raises the probability of ex post licensing by $47\%$. To summarize, ex post licensing is especially important for larger and more symmetric firm pairs to resolve hold-up problem.

Regarding the relevance of firms' patent stocks on the licensing decision, we find that pairs with larger average patent portfolios are less likely to license ex ante. This finding is interesting as it contrasts with the finding that larger firms in product markets are more likely to form licensing deals. 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 $21\%$.

Turning to the fragmentation of patent ownership, the estimates show, that an increase in fragmentation has a negative significant effect on ex ante and ex post licensing. We observe that fragmentation increased by over $0.4$ over the sample period. This corresponds to a smaller probability of observing ex ante and ex post licensing of 10%. This result highlights that the usefulness of both types of licensing may be limited where patent rights become increasingly fragmented so that a single licensing contract has limited effects.

As the potential for hold-up grows due to greater fragmentation of patent ownership, licensing might considered to be less useful in preventing hold-up. Hence, the trend towards greater fragmentation of patent rights undermines the importance of ex ante and ex post licensing

Finally, multimarket participation does not turn out to be significant. This result indicates that different product markets are characterized by dissimilar technologies, such that only little overlap in patent rights occurs causing little concerns for hold-up.

Table 5 displays the marginal effects based on our results shown in Table 4, columns (3) and (4). The table shows that the marginal effect of all our variables are highly significant, with the exception of multimarket participation.

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** |
| | (0.001) | (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 | -6.0·e-04 | -6.0·e-04 |
| | (0.059) | (0.001) |
| Previous ex post contracts | | -3.0·e-04*** |
| | | (6.0e-05) |
| Previous ex ante contracts | | 0.001*** |
| | | (1.0e-04) |

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

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

We turn now to consider the impact of ex ante licensing on firms' R&D investments.

### 5.2 Effects of Licensing on firms' R&D investments

Our theoretical model indicates that the type of licensing contract chosen by firms affects the intensity of patent portfolio races. Hypothesis 5 predicts that firms' R&D investments and the associated patenting efforts will be higher under ex post licensing than under ex ante licensing. In the following, we employ an endogenous switching model, accounting again for the fact that firms self-select into licensing deals.

#### The Endogenous Switching Model

The empirical specification closely follows the bivariate probit selection model, see equation (6). It consists of two equations: the selection and the outcome equation. The selection equation describes the decision to license ex ante, which is again treated as an endogenous binary decision variable. The specification of the selection equation is equivalent to the selection equation (2) in the bivariate probit selection model.

The outcome equation describes how ex ante licensing and other factors affect firms' patenting levels. Hence, the dependent variable in the outcome equation of the switching model is the number of patent applications ($A$).[25] The equation is specified as follows:

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

All variables are specified in the same way as in the bivariate probit model and identification of our endogenous switching model follows from the same exclusion restrictions employed in the bivariate probit selection model. The endogenous switching model is given by:

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

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[25] As demonstrated in Section 2, firms' patent stocks and the number of annual patent applications is rather large. We therefore treat the number of patents as a continuous variable. However, as a robustness check, we also treated the number of patent applications as a counter and estimated a Poisson model.

The assumptions on the error terms are the same as above. The equations are jointly estimated using FIML.

**Estimation Results**

Table 6 shows the parameter estimates for our switching model including the marginal effects for the selection equation. The results of our selection equation are very similar to our previous results shown in Table 4, column (3) and Table 5, column (2).

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*** | -2.0·e-04 | -3.48e-06* |
|  | (0.001) | (1.0e-04) | (0.000) |
| Differences in patent stocks | 0.008*** | 3.0e-05 | 4.18e-07 |
|  | (0.001) | (6.0e-05) | (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*** | -2.0e-04*** |
|  |  | (0.005) | (7.0e-05) |
| 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) |  |
| $\rho$ | 0.126*** |  |  |
|  | (0.043) |  |  |
| $\sigma$ | 31.98*** |  |  |
|  | (0.129) |  |  |

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

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

Turning to the results of our outcome equation shown in column (1), we find that ex ante licensing has a significant negative effect on the level of patenting. Ex ante licensing reduces the number of patents by $12.5$ patents, a $13\%$ reduction in the level of patenting. This result confirms our Hypothesis 5 and also provides further support that patent portfolio races are an important element of our theoretical model, i.e., firms' licensing decisions have a significant impact on patent portfolio races. Interestingly, we find that an increase in blocking reduces firms' patenting levels. A one standard deviation increase in blocking reduces firms' patenting by $4.4$ patents. At first glance, this result may seem puzzling since we would expect blocking to increase the level of patents as blocking is associated to an ongoing patent race and therefore related a a possible ex post licensing agreement. The underlying driver of our results in our theoretical model is based on the fact that firms drastically increased their R&D investments if they continued racing against the background of a high degree of blocking. However, comparing the reduction of patents due to an ongoing patent race ($4.4$ patents) with the reduction of patents in case of an ex ante licensing contract ($12.5$ patents), we find that an ongoing patent race generates ($8.1$) more patents. This result shows that firms not signing up for ex ante licensing enter a patent race and increase their patenting levels or investment in R&D. Ex ante licensing allows firms to avoid to drastically increase their R&D investments.

We also find that firms characterized by larger patent stocks produce more patents. An increase in patent stocks by one standard deviation causes an increase of $82$ or $84\%$ more patents. Furthermore, we show that greater fragmentation of patent ownership increases patent applications, which confirms the findings from Ziedonis (2004). An increase in fragmentation by $0.4$ raises the number of patent applications by $6.5$ patents ($6.5\%$). Finally, multimarket presence raises the number of patent applications by $6.5$ patents.

## 6 Conclusion

This paper focuses on analyzing the choice between ex ante and ex post licensing in an industry affected by a patent thicket. We use a data set on the semiconductor industry, which contains information on firms' licensing, patenting and production data. A first insight into the data reveals no significant relationships between patenting counts and licensing. While the number of patents more than doubles over time, the number of licensing contracts follows an inverse U-shape. This observation is surprising given the fact that Grindley and Teece (1997) argue licensing is mainly used to avoid hold-up. To gain further insights into firms' choices between ex ante and ex post licensing we develop a theoretical model of licensing in the context of patent portfolio races. The theoretical model shows that firms' choices between ex ante and ex post licensing depend on expectations and realizations of blocking and transaction costs. Furthermore, the model explains how the different types of licensing affect firms' R&D investments.

Our estimation results confirm most of our hypotheses derived from our theory. Ex ante licensing is an important instrument for firms if the expected degree of blocking in the technology space is high. Hence, ex ante licensing is an instrument that allows firms to reduce the competitive pressure originated from the intensity of patent portfolio races. In fact, we provide evidence that ex ante licensing significantly reduces the level of patenting. Ex post licensing will be signed if expected blocking is low and realized blocking is high. It is an important instrument for firms to resolve the hold-up problem and to exchange blocking patents. Importantly, ex post licensing appears to be more important for firms with large product market shares. Asymmetry of market shares reduces the likelihood that firms engage in licensing overall. Ex ante (ex post) licensing is an important instrument for more similar (dissimilar) firm pairs in technology.

One serious concern related to ex post licensing is that firms race for more blocking patents which serve the purpose of gaining a stronger bargaining position after the race. With respect to ex ante licensing, firms reduce their R&D investment. It would be interesting to examine whether the reduction in R&D investments would be socially suboptimal or not. However, this question is beyond the scope of this study and left for future research. Worryingly, our results illustrate that ex ante licensing is associated with significant contracting and transaction costs which seem to diminish with experience. Our study also stresses the fact that licensing becomes less important as patent ownership becomes more fragmented. Thus, a deepening of patent thickets resulting from more complex blocking relationships seems to undermine the usefulness of licensing to resolve blocking. Those aspects might be relevant for policy makers when determining the incentives for firms to cut through the patent thicket.

In general, we show that licensing is an important instrument for firms to cut through the patent thicket. We can confirm that "freedom to operate" Grindley and Teece (1997) is a central argument in understanding licensing in patent thickets. We also provide evidence that the distinction between ex ante and ex post licensing is essential to thoroughly understand firms' opportunities to resolve hold-up problems.

As patent thickets are likely to persist in the near future (von Graevenitz et al., 2008b), further research on the effects of licensing in complex technology industries seems warranted. In future research we intend to concentrate on the fragmentation aspect and plan on gaining a deeper understanding of more complex ownership relationships between firms holding blocking patents.

# Appendix

## A Empirical Robustness Checks

We replace our blocking variables which are based on information from firms' patents granted in the United States with an alternative measure of blocking. Our alternative blocking variable uses European patent data in which references to previous patents that block some or all of the subject matter in the patent under consideration are identified (von Graevenitz et al., 2008a, 2011). Using this information to measure blocking we exploit the equivalence of U.S. and European patents and run the same bivariate probit selection regression as above. Table 7 provides the results based on this alternative and more direct blocking variable.

Table 7: Coefficients for Bivariate Probit Selection Models of Licensing

| | Bivariate Probit | | Bivariate Probit | |
|---|---|---|---|---|
| Independent Variable | Pr (Ex post)<br>(1) | Pr (Ex ante)<br>(2) | Pr (Ex post)<br>(3) | Pr (Ex ante)<br>(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) |
| $\rho$ | -0.879*** | | -0.908*** | |
| | (0.145) | | (0.102) | |
| $-\ln L$ | -373.169 | | -373.349 | |

NOBS total=2,745.

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

The results are similar to those presented in Table 4 and confirm our earlier findings. Blocking and licensing experience carry the signs predicted by our model. This additional robustness check confirms our blocking measure from above. Note, since the equivalence of U.S. and European patents is rather small, the number of observations is significantly smaller than in Table 4. The small sample size might also explains why some of the product and technology market variables turn out to be insignificant.

## B A Model of Licensing in Patent Thickets

In this section, we present our theoretical model and derive the results which form the foundation of the hypotheses introduced in Section 3. We begin with introducing the assumptions and the structure of the model. Afterwards, we show how the values of ex post and ex ante licensing as well as the corresponding R&D investments change with respect to blocking.[26]

Our theoretical model focuses on the invention of a complex technology, which is characterized by the fact that multiple patents need to be acquired.[27] We assume that two firms are engaged in a patent portfolio race and invest in R&D. Firms commit to their R&D investments and apply open loop strategies.[28] R&D investments eventually turn into patents at a certain patent rate.

One firm starts to produce patents first and the corresponding period is denoted by $T_1$. We call this firm the winner from now onwards. The other firm (also called the loser, hereafter) is supposed to start patenting afterwards, at time period $T_2$. The time periods $T_1$ and $T_2$, are randomly distributed with the exponential distribution:

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

The variables $h_w, h_l$ denote firms' hazard rates or R&D investments of the winning and losing firm, respectively.[29] Note that $T_1$ and $T_2$ are independent. The interval between time periods $T_1$ and $T_2$ depends on the loser's R&D investments and refers to the time interval in which the winning firm accumulated a certain number of unblocked patents. From time period $T_2$ onwards, both firms continue racing and also continue producing patents. Part of their subsequently generated patents are likely to overlap. The overlapping patents represent the blocking patents. Blocking patents might hamper firms from successfully inventing a new technology and are the cause for the hold-up problem. The probability of facing blocking patents is given by $\beta$, where $\beta \in [0, 1]$.

The expected sizes of winner's ($Q_w$) and loser's ($Q_l$) portfolios that consist of entirely unblocked patents

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[26] Note that the model by Siebert and von Graevenitz (2010) is significantly different in various aspects, i.e., the endogeneity of blocking and R&D, the distinction between expected and realized blocking and the relationships between products in the product market.

[27] Note that even though firms are assumed to race for different technologies they still encounter the danger of facing blocking patents and running into a hold-up problem.

[28] This assumption builds on the fact that patent races are short, such that rivals' R&D efforts remain unobserved during the race. Moreover, Hall et al. (2005) show that it takes about 1.76 years to turn patent applications into granted patents. Therefore, firms would learn about their rivals' patents only with a substantial delay, which is too long to adjust a firm's research agenda in an ongoing patent portfolio race.

[29] In general, all variables pertaining to the winning and losing firm are denoted by the subscripts $w$ and $l$, respectively.

are:[30]

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

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

where $\lambda$ denotes the rate of patenting, and $r$ is the interest rate.[31] A higher research effort chosen by the loser will move time period $T_2$ closer to time period $T_1$ and reduce the ex post asymmetry between firms' patent portfolios.

Each firm has the opportunity to engage in licensing agreements in order to exchange their blocking patents which allows firms to complete their invention. Note, that licensing is not modeled as an R&D cooperation with the purpose to jointly explore new technologies. Instead, it is formulated as an instrument that allows firms to exchange blocking patents and to reduce the threat of hold-up in patent thickets.

We distinguish between two types of licensing agreements. In an ex post licensing agreement, firms exchange their blocking patents after completing the portfolio race, i.e., in stage 3. Firm's size of patent portfolios will determine their bargaining strength, see also Grindley and Teece (1997); Lemley (2001); Hall and Ziedonis (2001); Ziedonis (2004). Alternatively, firms can sign an ex ante licensing agreement, in which they commit at the beginning of the game to exchange all blocking patents generated throughout the patent race.

We embed the patent portfolio race into a three stage model, which incorporates the decision to license ex ante or ex post: Stage One: Both firms simultaneously choose whether to sign an ex ante licensing contract. Stage Two: Both firms invest in R&D and obtain patents. One firms start patenting in period $T_1$, the other firm begins to patent in period $T_2$. Stage Three: Given firms did not sign an ex ante contract, they choose whether to bargain over an ex post licensing contract, or not to license. This model is solved by backward induction. We now turn to describe firms' profits: before firms engage into the patent portfolio race, they are symmetric and earn profits $\pi_0$. After the race, profits depend on the number of unblocked patents in each firm's own and in its rival's patent portfolios, i.e., the extent to which these guarantee "freedom to operate" : $\pi_i(Q_i, Q_j)$ where $i; j$ are subscripts denoting the firm under consideration ($i$) and its rival ($j$). In particular, a firm's profit is increasing in the size of its own patent portfolio. Rivalry implies a negative effect of the size of the rival's patent stock on a firm's profit. 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:

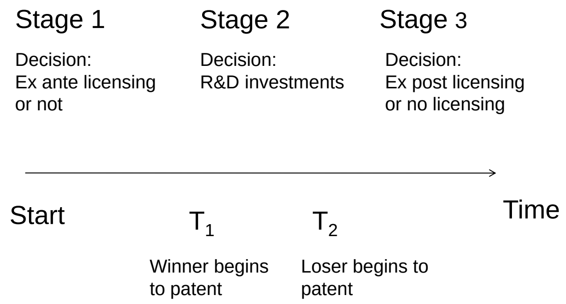
$$\frac{\partial^2 \pi_i(Q_i,Q_j)}{\partial Q_i \partial Q_j} > 0 \quad . \tag{S}$$

---

[30] The portion of patents that consists of unblocked patents is the full stream of patents that was generated before time period $T_2$ and the fraction $(1-\beta)$ of patents generated after period $T_2$.

[31] For clarification, the winner patents at a rate $\lambda$ from time period $T_1$ onwards. The loser patents at this rate after time period $T_2$.

Figure 6: Timing of the Patent Portfolio Race



This assumption implies that a firm's marginal benefit from acquiring additional patents is increasing in the size of the rival's patent portfolio. This assumption emphasizes that the relative size of firms' patent portfolios determines bargaining strength (Lemley, 2001).[32]

Firms' (net) profits after R&D are given by $V_i = \pi_i - \gamma(h_i)$. We impose standard restrictions on firms' R&D costs:

$$\text{(i) } \gamma(0) = \gamma'(0) = 0,\ \gamma''(0) > 0 \qquad \text{(ii) } \forall h > 0,\ \ \gamma(h) > 0,\ \gamma'(h) > 0,\ \gamma''(h) > 0$$

$$\text{(iii) } \lim_{h \to \infty} \gamma'(h) = \infty \quad . \tag{G}$$

The restrictions imply, that: $(i)$ 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.

Next, we show how the value of ex post licensing and the corresponding R&D investments depend on blocking.

## B.1 Ex post Licensing

An ex post licensing contract removes hold-up and provides firms with “freedom to operate”İn this case, the degree of blocking $\beta$ is zero and the patent portfolios are:[33]

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

$\bar{Q}$ refers to the special case when firms face no blocking at all. This represents the upper bound of each firm's patent stock. We assume that the licensing contract signed by the firms conforms to the outcome of a Nash bargaining game. This implies that the party which has a stronger bargaining position receives some of the surplus generated by the licensing contract in the form of a payment. Grindley and Teece (1997) confirm the existence of such payments as do our data. Under Nash bargaining the winner's and loser's payoffs (before R&D costs) are:

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[32] A simple example of a profit function which fulfills assumptions (P) and (S) is: $\pi_i = \log(Q_i) - \log(Q_i + Q_j)$.

[33] Contrast firms' patent portfolios in our case with firms' patent stocks under the standard assumption in common patent race models. In the latter case, firms exchange technologies such that both firms' patent stocks comprise all new patents: $\bar{Q} = \frac{\frac{\lambda}{r}(2h_l + r)}{h_l + r}$.

$$v_w = \tfrac{\triangle\pi}{2} + \tfrac{1}{2}\Big[\pi(\bar{Q}_w, \bar{Q}_l) + \pi(\bar{Q}_l, \bar{Q}_w)\Big] \qquad v_l = -\tfrac{\triangle\pi}{2} + \tfrac{1}{2}\Big[\pi(\bar{Q}_w, \bar{Q}_l) + \pi(\bar{Q}_l, \bar{Q}_w)\Big] \ , \tag{12}$$

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 $v_w - v_l = \triangle\pi$ represents the premium for the winner, or the firm that began patenting first.

The value function describing the expected return from a patent portfolio race is:[34]

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

where the subscript $p$ refers to ex post licensing. The hazard rates chosen by the firm under consideration is denoted by $h_p$, and the hazard rate chosen by the rival firm is given by $H_p$. Note, that the expected values of winning and losing are functions of firms' research efforts: the expected value of winning the patent portfolio race declines in the opponent's (loser's) investments $(H_p)$ and the expected value of losing increases in own investments $(h_p)$.[35]

**R&D Investment**

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

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

It can be shown that:

**Proposition 1**

*The patent portfolio race is a smooth supermodular game.*

In order to show the supermodularity, we consider the first order condition with respect to own R&D investments as well as the cross-partial derivative with respect to the rival firm's R&D investments. The first order condition is given by:

$$\begin{aligned} \frac{\partial V_p}{\partial h_p} = \frac{1}{(h_p + H_p + r)^2}\Bigg[ & \underset{\text{comp. threat}}{\frac{(v_w - v_l)}{r} H_p} + \underset{\text{profit inc.}}{[v_w - \pi_0]} + \underset{\text{symmetry inc.}}{\frac{\partial v_l}{\partial h_p}\frac{H_p}{r}(h_p + H_p + r)} \\ & + \gamma(h_p) - \gamma'(h_p)\left[h_p + H_p + r\right] \Bigg] = 0. \end{aligned} \tag{15}$$

---

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

[35] This feature distinguishes this value function from those in patent race models in the tradition of Lee and Wilde (1980).

Three incentives determine each firm's R&D investments. The competitive threat captures the value of winning rather than losing. The profit incentive illustrates the benefit of winning sooner rather than later.[36] Both incentives are positive as winning the patent portfolio race further enlarges the patent portfolio, which increases profits according to assumption (P). Finally, the symmetry incentive is new to our model and captures the increased symmetry of winner and loser if the latter invests more. In the following, we show that the symmetry incentive is positive. Consider the following first order condition:

$$\begin{aligned}\frac{\partial v_l}{\partial h_p} = \frac{\lambda}{2(h_p+r)^2}\Big[&\frac{\partial \pi(Q_l,Q_w)}{\partial Q_l}\beta - \frac{\partial \pi(Q_l,Q_w)}{\partial Q_w}(1-\beta) + \frac{\partial \pi(Q_w,Q_l)}{\partial Q_w}(1-\beta) \\ &- \frac{\partial \pi(Q_w,Q_l)}{\partial Q_l}\beta + \frac{\partial \pi(\bar{Q}_l,\bar{Q}_w)}{\partial \bar{Q}_l} + \frac{\partial \pi(\bar{Q}_w,\bar{Q}_l)}{\partial \bar{Q}_l}\Big] > 0 \quad . \qquad (16)\end{aligned}$$

First, note that in the absence of blocking $v_l = \pi(\bar{Q}_l,\bar{Q}_w)/r$. Since greater R&D effort ($h_p$) increases the size of the loser's patent portfolio $Q_l$ and their expected profits, (16) is positive when there is no blocking. As blocking increases, the marginal value of R&D investment to the loser increases. This follows from the supermodularity of the profit function and assumption (P) and is shown now. Effects of blocking on marginal value of own R&D investment:

$$\frac{\partial^2 V_p}{\partial \hat{h}\partial\beta} = \frac{1}{(2\hat{h}+r)}\left[\frac{\partial \triangle\pi}{\partial\beta}\frac{(\hat{h}+r)}{(2\hat{h}+r)} + \frac{\partial^2 v_l}{\partial h_p \partial\beta}\frac{\hat{h}_p}{r}\right] \quad . \qquad (17)$$

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

$$\frac{\partial \triangle\pi}{\partial\beta} = -\frac{\lambda}{2r}\frac{\hat{h}_p}{\hat{h}_p+r}\Big[\underbrace{\frac{\partial \pi(Q_w,Q_l)}{\partial Q_w} + \frac{\partial \pi(Q_w,Q_l)}{\partial Q_l} - \frac{\partial \pi(Q_l,Q_w)}{\partial Q_l} - \frac{\partial \pi(Q_l,Q_w)}{\partial Q_w}}_{\nu}\Big] \qquad (18)$$

$$\begin{aligned}\frac{\partial^2 v_l}{\partial h_p\partial\beta} =& \frac{\lambda}{2(h_p+r)^2}\Big[\underbrace{\frac{\partial \pi(Q_l,Q_w)}{\partial Q_l} + \frac{\partial \pi(Q_l,Q_w)}{\partial Q_w} - \frac{\partial \pi(Q_w,Q_l)}{\partial Q_w} - \frac{\partial \pi(Q_w,Q_l)}{\partial Q_l}}_{-\nu}\Big] \qquad (19)\\ -\frac{\lambda^2}{2r(h_p+r)^3}&\left[\underbrace{\frac{\partial^2 \pi(Q_l,Q_w)}{\partial {Q_l}^2}\beta - \frac{\partial^2 \pi(Q_l,Q_w)}{\partial {Q_w}^2}(1-\beta) + \frac{\partial^2 \pi(Q_w,Q_l)}{\partial {Q_w}^2}(1-\beta) - \frac{\partial^2 \pi(Q_w,Q_l)}{\partial {Q_l}^2}\beta}_{\omega}\right.\\ &\left.\underbrace{-\frac{\partial^2 \pi(Q_l,Q_w)}{\partial Q_w\partial Q_l}(1-2\beta) + \frac{\partial^2 \pi(Q_w,Q_l)}{\partial Q_w\partial Q_l}(1-2\beta)}_{\zeta}\right].\end{aligned}$$

Supermodularity of the profit function implies that the third element of $\nu$ 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

---

[36] The competitive threat is also called replacement effect and the profit incentive is also called the efficiency effect in the literature on innovation, see e.g., Reinganum (1989); Beath et al. (1994).

(P) also implies that $\omega$ is negative. Finally, local stability of equilibrium requires that the cross partial effects ($\zeta$) are smaller in absolute value than the second derivatives that are components of $\omega$. 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 in R&D.

As R&D investment brings forward the date at which the loser begins to patent and improves his bargaining position, equation (16) is positive for all values of $\beta$. Consequently, blocking increases firms' R&D investments.[37]

Now, consider the cross-partial derivative with respect to firms' own and rivals' R&D investments:

$$\frac{\partial^2 V_p}{\partial h_p \partial H_p} = \frac{1}{(h_p + H_p + r)^2}\left[\frac{(v_w - v_l)}{r} + \frac{\partial v_l}{\partial h_p}\frac{1}{r}(h_p + 2H_p + r) + \frac{\partial v_w}{\partial H_p}\frac{1}{r}(H_p + r) - \gamma'(h_p)\right] > 0 \quad . \tag{20}$$

Making use of the first order condition (15) to substitute out terms and inserting $V_p$ as defined in equation (13), we can rewrite (20) as follows:

$$\frac{\partial^2 V_p}{\partial h_p \partial H_p} = \frac{1}{(h_p + H_p + r)^2}\left[V_p - \frac{v_l}{r} + \frac{\partial v_l}{\partial h_p}\frac{1}{r}(h_p + H_p + r) + \frac{\partial v_w}{\partial H_p}\frac{1}{r}(H_p + r)\right] > 0 \quad . \tag{21}$$

Consider the terms 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 $v_l$ as shown in equation (12) it is apparent that:

$$\frac{\partial v_l}{\partial h_p} = -\frac{\partial v_w}{\partial H_p} \quad . \tag{22}$$

Hence, given the symmetry incentive is positive, equation (21) must be positive. As a consequence of equation 15 and equation 20 being positive, the game defined above equation (14) is smooth supermodular (Milgrom and Roberts, 1990; Vives, 1999).

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

**Proposition 2**

*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 equation (14) in our supermodular game. Then, the expected value of ex post licensing equation (13) is:

$$V_p(\hat{h}_p) = \frac{\frac{v_w + v_l}{r}\hat{h}_p + \pi_0 - \gamma(\hat{h}_p)}{2\hat{h}_p + r} \quad . \tag{23}$$

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

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

$$\frac{\partial V_p(\hat{h}_p)}{\partial \beta} = -\frac{1}{2\hat{h}_p + r}\left[V_p - \frac{v_l}{r} + \left(\frac{\partial v_l}{\partial \hat{h}_p} - \frac{\partial \pi(\bar{Q}_l, \bar{Q}_w)}{\partial \hat{h}_p} + \frac{\partial \pi(\bar{Q}_w, \bar{Q}_l)}{\partial \hat{h}_p}\right)\frac{\hat{h}_p}{r}\right]\frac{\partial \hat{h}_p}{\partial \beta} < 0 \quad . \tag{24}$$

The first component is the effect of greater R&D efforts on the expected value of ex post licensing as represented inside the round brackets of equation (24). It is easily shown that this effect is negative: First, consider the case in which there is no blocking. Then, the sum of derivative terms in equation (24) is $-\partial \pi(\bar{Q}_w, \bar{Q}_l)/\partial h_p > 0$. Consider now an increase in blocking. In equation (19) above, we have shown that increased blocking raises marginal returns to R&D investments for the loser. Hence, it follows that the first component of equation (24) is positive for any degree of blocking.

The second component is the last term in equation (24) and describes the effect of blocking on firms' R&D investments. To sign this effect we derive the cross-partial effect of blocking and research efforts. Milgrom and Roberts (1990) show the sign of cross-partial effects determine the sign of a comparative statics effect in supermodular games.[38] Given assumptions (S) and (P) we show that:

**Proposition 3**

*An increase in blocking raises firms' equilibrium R&D efforts ($\hat{h}$).*

This has been shown above, see equation (19).

Finally, note that Propositions 2 and 3 result in Proposition 1. Moreover, as greater blocking induces greater R&D efforts and these reduce the value of ex post licensing, we can derive the following proposition:

**Proposition 4**

*A higher degree of blocking lowers the expected value of ex post licensing ($V_p$).*

We now turn to ex ante licensing agreements.

### B.2 Ex ante Licensing

While the value of ex post licensing declines in the realized degree of blocking, the value of ex ante licensing is not affected by the realized degree of blocking; it rather depends on the expected degree of blocking.[39] In case firms sign an ex ante licensing contract, they agree to make their inventions available to each other. Consequently, the degree of realized blocking is zero and no hold-up occurs. If the realized degree of blocking is zero, firms' expected patent portfolios are $\bar{Q}_w$ and $\bar{Q}_l$ as shown above and 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 5**

*If firms expect zero blocking, the values of ex ante and ex post licensing are identical: $V_a = V_p$.*

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[38] Since firms' R&D investments are strategic complements and the game is smooth supermodular, we are able to apply comparative statics to our value functions.

[39] Remember that, by definition, ex ante licensing consists of a contract that prevents blocking.

In order to show that Proposition 5 holds, we consider the value function under ex ante licensing:

$$V_a(0, \pi_0, h_a, H_a) = \frac{\frac{v_w(H_a,0)}{r} h_a + \frac{v_l(h_a,0)}{r} H_a + \pi_0 - \gamma(h_a)}{h_a + H_a + r} \quad . \tag{25}$$

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

$$\frac{\partial V_a}{\partial h_a} = \frac{1}{(h_a + H_a + r)^2} \Bigg[ \underset{\text{comp. threat}}{\frac{(v_w - v_l)}{r} H_a} + \underset{\text{profit inc.}}{[v_w - \pi_0]} + \underset{\text{symmetry inc.}}{\frac{\partial \pi(\bar{Q}_l, \bar{Q}_w)}{\partial h_a} \frac{H_a}{r} (h_a + H_a + r)} \\ + \gamma(h_a) - \gamma'(h_a) \left[ h_a + H_a + r \right] \Bigg] = 0 \quad . \tag{26}$$

This expression indicates that the R&D investment game is also smooth supermodular in the ex ante licensing case. Equation (26) shows that the first order condition in ex ante licensing is equivalent to the first order condition in ex post licensing without blocking, equation (15). Then, Proposition 6 follows from Propositions 2, 3 and 5 and keeping in mind that blocking is zero in the ex ante licensing case. Hence, we can derive our main result:

**Proposition 6**

*A higher degree of realized blocking reduces the value of ex post licensing relative to ex ante licensing.*

To summarize, our theoretical model shows how blocking affects firms' licensing behavior. As shown in Proposition 5, if blocking ($\beta$) is zero, the expected values of ex ante licensing ($V_a$) and ex post licensing ($V_p$) are equal. We also show in Propositions 2 and 3 that as the probability of blocking patents arising increases, the expected value of ex post licensing is strictly less than that of ex ante licensing $V_a(\beta) > V_p(\beta) \; \forall \; \beta > 0$. Hence, the model predicts that firms strictly prefer ex post licensing to ex ante licensing if blocking is larger than zero. Consequently, we should observe almost exclusively ex ante licensing in our data, because this avoids overinvesting in R&D when firms enter the patent portfolio race. Recall that we did not account for fixed transaction or contracting costs that reflect organizational and legal efforts, which need to be incurred by the firms when they sign licensing agreements. Those costs, however, would be necessary when designing the contracts.

Once we account for the fact that firms have to incur transaction costs, the prediction from Proposition 6 might change. If there is a low probability of facing a high degree of blocking, then it is unlikely that firms sign an ex post licensing contract, as they can save on transaction costs. If the firms signed an ex ante contract instead, those transaction costs had to be payed with certainty at the beginning of the game. Therefore, in case the probability of discovering blocking patents is sufficiently low, firms will prefer not to engage in ex ante licensing. In case, expected blocking is low and realized blocking eventually turns out to be high, firms will sign ex post licensing contracts. Therefore, we can conclude that if expected blocking is low and realized blocking is high, firms will sign ex post licensing agreements. If expected blocking is high, firms engage in ex ante licensing to avoid engaging in patent races which drastically increases R&D investments.

It is interesting to note, that in our model firms' decisions to engage into a type of licensing does not arise from sharing R&D costs which is a common explanation in models of R&D cooperation Röller et al. (2007). It is rather based on the finding that firms engage in patent races under ex post licensing and drastically increase R&D investments, which lowers the value of ex post licensing.

Finally, we turn to a comparison of firms' incentives to invest in R&D under ex ante and ex post licensing. Remember, Proposition 3 shows that increases in blocking have the effect of raising firms' R&D investments in ex post licensing. R&D incentives under ex ante licensing are weaker than those under ex post licensing. We therefore expect a lower patenting rate, or fewer patents being issued under ex ante licensing.

## 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 Data

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 and 1999. 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 date on which the licensing contract was signed, the participating firms and a synopsis indicating the technology, the purpose and the type of licensing, i.e., whether firms signed ex ante or ex post licensing contracts. 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 more than $98\%$ of the contracts were unambiguously classified into ex ante or ex post licensing contracts. In only $2\%$ of the cases licensing contracts were categorized into ex ante and ex post licensing deals. 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. For consistency with our theoretical model our empirical analysis of licensing is restricted to horizontal technology licensing. Hence, we have excluded vertical partnerships 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 licenses. Finally, we dropped another 22 licensing contracts which were related to litigation. This left us with $847$ contracts over the whole time span.

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.[40] The

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[40] Rowley et al. (2000) study strategic alliances whereas we study licensing contracts. Our definition of a licensing contract is

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. The similarity of our dataset to other datasets reinforces our confidence in the results we presented above.

**Examples for Ex Ante and Ex Post Licensing** This section contains examples of licensing contracts taken from our data set.

**Ex Ante Licensing**

- Date: 01/01/1989. Texas Instruments Inc. and Hitachi Ltd. terminated their former strategic alliance. In a three year pact, Texas Instruments, Inc. (TI) and Hitachi Ltd. agreed to share technologies for producing 16 MB Dynamic Random Access Memory (DRAM) chips. All licensing agreements will stay intact. The two companies will share all new data relevant to the next generation chips. TI and Hitachi cited high costs and risks associated with developing such chips as reasons for joining forces.

**Ex Post Licensing**

- Date: 03/15/1991. Advanced Micro Devices (AMD) and Atmel Corp. have signed a cross-licensing agreement regarding the two companies' patents. Atmel granted AMD a license to its patent portfolio, including those for non-volatile memory technology. In return, AMD granted Atmel a license for its own patent portfolio, excluding AMD's new MACH family of CMOS programmable logic devices. As part of the agreement, Atmel will also pay AMD an undisclosed royalty fee for future and past use of AMD's patents relating to its 22V10- type user-programmable logic circuits.

### C.2 Patents

In order to capture firms' positions in technology space we use information on granted patents.[41] 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 et al. (2005).[42] 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.

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any contract that also includes an agreement to license technology. Therefore, both studies focus on a similar set of agreements between firms.

[41] 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.

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

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 United States Patent and Trademark Office (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. Based on the classifications provided by the USPTO and Hall et al. (2005) and we chose those patent classes that represent memory chips, microcomponents and other semiconductor devices.

As the patent database lasts only until 1999, we need to account for truncation issues. Therefore, our patent related 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 $U.S.$ dollar 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 have firm-level market share information for different semiconductor market segments: memory chips, microcomponents, and other devices.

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