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Does Licensing Resolve Hold Up in the Patent Thicket?

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Abstract

In a patent thicket licensing provides a mechanism to either avoid or resolve hold up. We study the choice between ex ante licensing to avoid hold up and ex post licensing to resolve it. Firms' choice of licensing contract is studied in the context of a patent portfolio race. We show that high expected blocking leads to ex ante licensing while ex post licensing arises if expected blocking is low but realized blocking is high. Also, ex ante licensing reduces firms' R&D incentives. A sample selection model of licensing is derived from the theoretical model. In this framework theoretical predictions on effects of blocking are tested with data from the semiconductor industry. We show that licensing helps firms to resolve blocking. However, licensing is not a cure all: it decreases as fragmentation of property rights increases and arises mainly between large firms with similar market shares. Using a treatment effects model we also confirm the prediction that ex ante licensing reduces the level of R&D investment.

JEL: L13, L49, L63.

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

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1 Introduction

In some high technology industries the process of research and development is comparable to the continuous extension of a pyramid through the addition of new building blocks at the top [Shapiro (2001)]. Here, the pyramid serves as a metaphor for the cumulativeness of scientific research in complex product industries.[1]

Firms increasingly protect their contributions to this pyramid with patents. As a result several high technology industries are now affected by a "patent thicket" [Heller and Eisenberg (1998); Hall and Ziedonis (2001); Shapiro (2001)]. In a patent thicket many rival firms hold patents protecting components of a single technology. Whenever a firm uses such a technology it is vulnerable to hold up by firms holding blocking patents [Grindley and Teece (1997), Jaffe (2000), Shapiro (2001)]. The threat posed by blocking patents frequently induces firms to build up a large portfolio of patents. This creates a strong bargaining position for the firm owning the portfolio in any disputes with rivals. In a patent thicket all firms face the prospect of hold up and have strong incentives to patent, which perpetuates the patent thicket. Hold up in a patent thicket may be resolved through licensing of blocking patents. Therefore, an understanding of how licensing works in industries affected by patent thickets is increasingly important.

We study how licensing is employed to resolve hold up using data on licensing contracts between semiconductor firms. Licensing contracts signed before R&D investments take place (ex ante contracts) are distinguished from those signed after such investments turn into granted patents (ex post contracts). Our data show licensing contracts are often forward looking (ex ante contracts).[2] Furthermore, changes which we observe in the level of total licensing activity between 1988 and 1998 are almost entirely due to changes in the level of ex ante licensing. Economic theory suggests that R&D incentives under ex ante licensing differ from those under ex post licensing. We study the choice between ex ante and ex post licensing to examine the implications of patent thickets for firms' R&D incentives.

An ex post licensing contract will be preceded by a "patent portfolio race" [3] in which firms acquire as many patents as possible on the new technology. Firms' R&D incentives are high in this setting and licensing resolves blocking only once both firms have sufficiently

[1] A complex product is one which is based on many patents [Levin et al. (1987)]. Recently Cohen et al. (2000) show that firms in complex product industries primarily use the patent system for the purpose of forcing negotiations over access to others' patents.

[2] Examples of ex ante licenses may be found in Appendix B.

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

large portfolios to contract. In contrast an ex ante licensing contract allows firms to guarantee each other "freedom to operate" [Grindley and Teece (1997)] before R&D investments are made. The use of all patents included in the contract is assured for both parties: blocking has no effect. This removes an important incentive to acquire patents on the technology. In Siebert and von Graevenitz (2006) we develop a theoretical model of a patent portfolio race and licensing in an industry affected by a patent thicket. We study how variation in exogenous blocking affects licensing and R&D investment choices. Below we adapt that model, partly endogenizing the degree of blocking.

In our model the patent portfolio race between any two firms is a supermodular game. Firms' R&D expenditures are strategic complements. We show that exogenous increases in the degree of blocking increase firms' efforts to win the patent portfolio race. This has the perverse effect of reducing the expected amount of unblocked patents which firms obtain, further increasing the problem of blocking patents. To prevent very intense patent portfolio races and associated high levels of blocking firms may enter into ex ante licensing contracts.

Theoretical work on licensing has concentrated on licenses accompanying technology transfer [Scotchmer (2004); Gallini and Scotchmer (2004)]. In such models efficiency gains arise when firms share technologies. In the context of the patent thicket Grindley and Teece (1997) emphasise an alternative explanation for licensing: to assure "freedom to operate". This also implies efficiency gains as the threat of hold up within the patent thicket is removed.

The main contribution of this paper is empirical. We test effects of expected blocking and realized blocking on firms' licensing choices. We confirm that effects of blocking and licensing predicted by our model of patent portfolio races are present in data from the semiconductor industry. These results provide further evidence for patent portfolio races in this complex technology. We also find increased fragmentation of patent ownership as defined by Ziedonis (2004) reduces the likelihood of ex ante licensing: growing patent thickets undermine at least one option firms have to reduce the problem of hold up. Also, licensing is mostly undertaken by firms with large market shares confirming the findings of Galasso (2007). Finally, we find that ex ante licensing significantly lowers firms' patenting levels.

We use a dataset of licensing contracts announced between 1989 and 1999 in the semiconductor industry. A growing number of recent papers provide evidence of an emerging patent thicket in this industry [Grindley and Teece (1997); Shapiro (2001); Hall and Ziedonis (2001); Ziedonis (2004)]. Anand and Khanna (2000), who undertake a large sample study of licensing, also find that the semiconductor industry has one of the highest levels of licensing activity. 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.

The licensing data we study are puzzling: they show that overall licensing activity does not increase proportionally to the number of granted semiconductor patents. If more granted patents raise opportunities for hold up such a proportional increase might be expected. Licensing activity increases strongly after 1989 and then falls quite sharply after 1994, even though patent grants increase over the whole sample period. The data also show that ex ante licensing is far more prevalent and volatile than ex post licensing. This last finding is somewhat surprising since previous literature on patent thickets has focused on ex post licensing or the formation of patent pools as a means of resolving the threat of hold up [Grindley and Teece (1997); Shapiro (2001)]. Further investigation reveals that variation in the blocking may explain a large part of these trends.

As we cannot directly observe firms' R&D spending, a structural test of our model is out of reach. Instead, we develop a latent variable representation of the choice between ex ante licensing, ex post licensing and no licensing. In this model ex ante licensing is a function of expected blocking. Firms will choose not to license and enter into a patent portfolio race if expected blocking is low. If blocking turns out to be higher than expected, ex post licensing provides firms with an solution to blocking. The sequential nature of decisions on ex ante and ex post licensing can be represented using a bivariate probit sample selection model. Additionally, we show that the effects of ex ante licensing on the level of firms' patent applications can be modelled using a treatment effects model. Here ex ante licensing is the binary endogenous variable. We control for the endogeneity of the ex ante licensing decision by adapting the selection equation of the sample selection model.

The remainder of the paper is organised as follows: in Section 2 we describe licensing trends in the semiconductor industry. In Section 3 we introduce our theoretical model. In the following section we discuss its empirical implementation. Then in Section 5 we discuss our results. Finally, Section 6 concludes.

2 Licensing in the semiconductor industry

In this section we describe observed licensing behaviour. We constructed a dataset comprised of 921 licensing contracts between 268 firms. It contains information about the date, the partners and the purpose of the license as well as data on firms' revenues, market shares and patents. A detailed description how the data were constructed is provided in Appendix A.

In this section we describe the data and determine whether the blocking strength of firms' patent portfolios explains the choice of licensing contract by a pair of firms. We focus on firm pairs as the majority of contracts in our data are between pairs of firms. Where a contract is formed by three or more parties we treat it as a collection of simultaneous bilateral contracts among a group of firms.

Figure 1a

Growth of revenues and firm numbers in the semiconductor industry

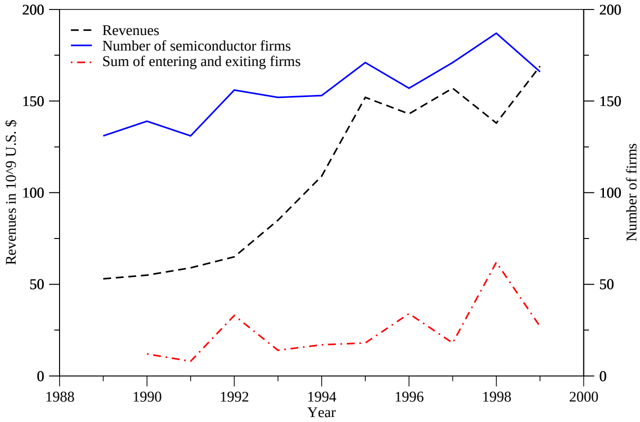


Figure 1b

Licensing and patenting activity in the semiconductor industry

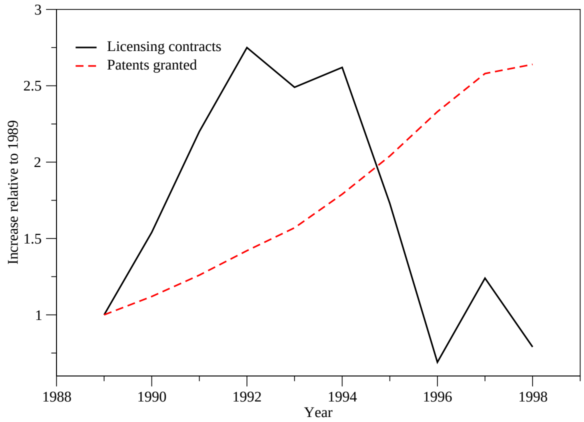


Figure 1a shows that total revenues of all semiconductor firms grew substantially over the period of our sample. Mirroring this there was also a large increase in the number of active semiconductor firms. However the figure also demonstrates that aggregate revenue almost stopped growing after 1996. This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

The semiconductor industry also experienced a strong surge in patenting activity after 1985 [Hall and Ziedonis (2001); Ziedonis (2003, 2004)]. Figure 1b provides information on the level of granted patents and licensing contracts relative to 1989. The number of new patents granted to semiconductor firms more than doubled over the period of our sample. This development has been carefully investigated by Hall and Ziedonis (2001) who argue that it is due to strategic patenting in the face of an emerging patent thicket. Surprisingly, the increase in patenting by semiconductor firms does not lead to a proportionate increase of licensing amongst these firms. As Figure 1b shows the number of new licensing contracts amongst semiconductor firms in our sample shows no obvious relation to the increase in granted patents. This is surprising because we might expect there to be a greater need for licensing as the number of patents grows.[4]

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

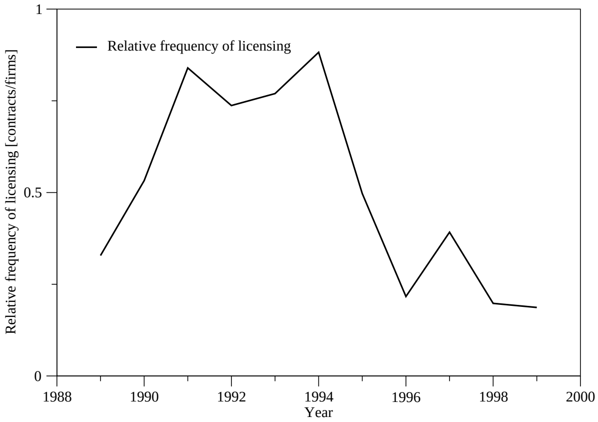


Figure 2b
Total ex ante and ex post licensing contracts in the semiconductor industry

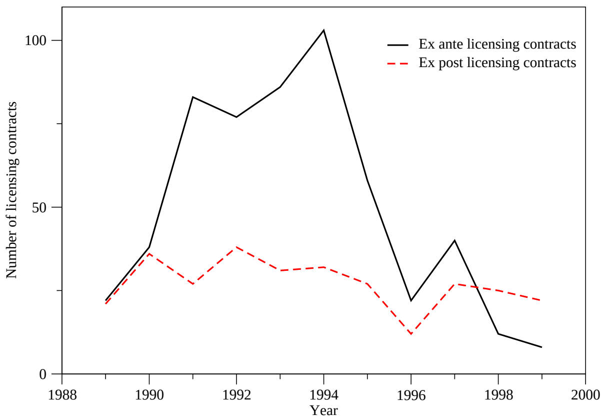


Figure 2a above shows the average number of licensing contracts per firm in the semiconductor industry. The figure displays a hump shape just as the absolute number of licensing contracts does. This rules out an explanation of the number of licenses based on the number of semiconductor firms. Between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

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

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

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

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.

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

Table 1 shows that Texas Instruments and Intel account for over one fifth of all ex post licensing agreements.[6] Previous studies [Grindley and Teece (1997); Shapiro (2001, 2003b)] tended to focus on these firms which may explain why they devote less attention to ex ante licensing. The number of ex ante licensing agreements is spread relatively evenly across the represented firms. In spite of this difference between ex ante and ex post licensing it is clear that nearly all of the represented firms engage in both types of licensing to a significant degree. Twenty nine percent (29%) of the contracts in our sample are signed by firms with experience of both ex ante and ex post licensing.

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

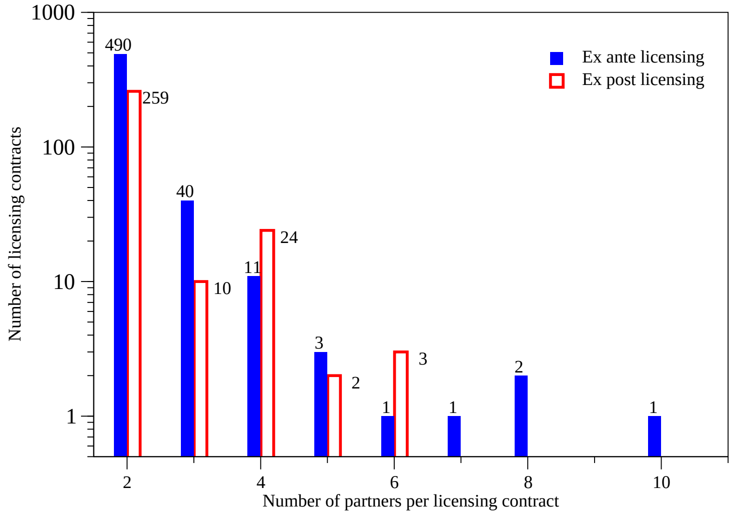
Table 1 suggests that there are differences in the semiconductor firms that choose ex ante and ex post licensing contracts. In order to further investigate this Table 2 provides a comparison of all firms that undertook ex ante and ex post licensing. This comparison does not reveal differences between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

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

To pursue the comparison of ex ante and ex post licensing we also investigate the number of firms involved in each licensing contract. As the histogram in Figure 3 illustrates, the vast majority of contracts in this sample are bilateral.

Figure 3

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



Overall these comparisons of firms engaged in ex ante and ex post licensing suggest that the observed trends are not the result of greater licensing activity by a group of firms specialising in ex ante licensing; rather, we must focus on the choice that all firms make between ex ante and ex post licensing. Furthermore an aggregate measure of the strength of the patent thicket, in form of patent counts, does not explain the development of licensing between semiconductor firms in aggregate. Neither is this measure related to the choice between ex ante and ex post licensing. In order to explain the observed differences in the propensity to choose ex ante and ex post licensing contracts we now turn to measures of the patent thicket at the level of firm pairs engaged in licensing. In other words we move from a focus on individual firms to a focus on firm pairs.

Figure 4a presents a measure of blocking between firms in a pair. We construct all possible firm pairs between firms with positive market shares in the semiconductor industry. For these pairs we construct a measure of blocking by interacting a measure of technological proximity with a measure of cross citations within the pair.[7] If firms patent in similar technology classes with the same intensity and cite each other frequently this measure is high. Figure 4a reveals that blocking initially increased and then decreased again over the sample period. The decrease is largely the result of the larger number of semiconductor firms which causes the number of potential pairs to rise significantly. Many of the pairs formed with

[7]For a precise definition of this measure refer to Section 4.2 below.

new entrants into the industry exhibit low levels of blocking as we would expect. Figure 4a indicates that blocking may provide a large part of the explanation for the development of licensing discussed previously.

Figure 4a

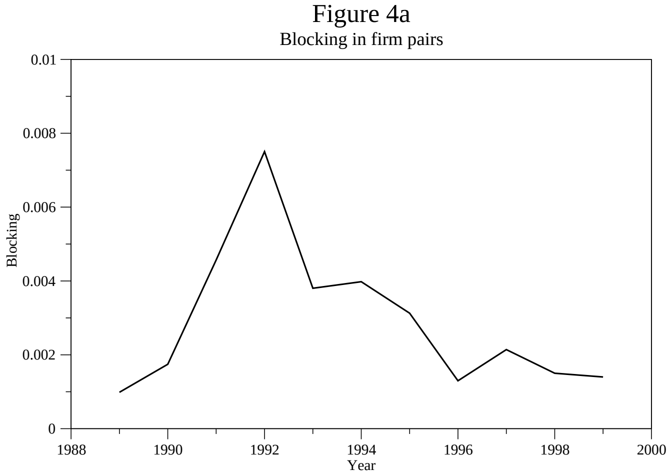


Figure 4b

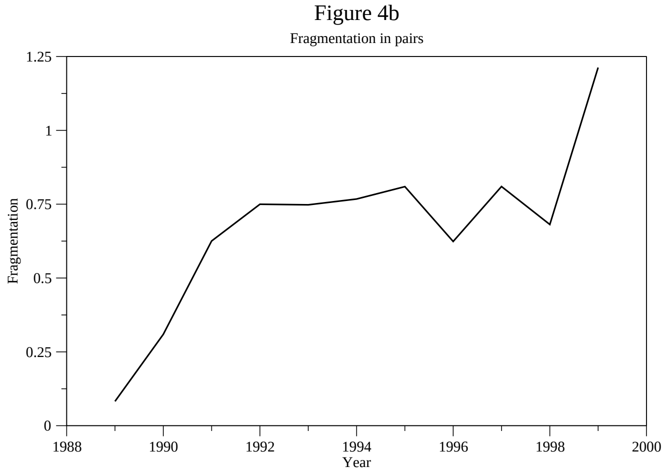


Figure 4b presents the development of fragmentation of technology ownership based on the citations from the patents held by a firm pair. Ziedonis (2004) shows that fragmentation explains some of the large increase in patenting levels in the semiconductor industry. She argues that the fragmentation index represents a measure of hold up potential. If licensing contracts resolve such potential we might expect licensing to be correlated with fragmentation. Figure 4b does not reveal a very clear relationship however.

In the following section we provide a theoretical model that seeks to clarify how blocking of patents arises in patent portfolio races. We investigate whether such blocking leads firms to license patents and how blocking is related to the choice between ex ante and ex post licensing. The model is then tested in the following sections.

3 A model of licensing in the patent thicket

In this section we provide a model of patenting and licensing behaviour of firms using complex technology. The model yields predictions about the effects of anticipated blocking on firms' R&D investments and their licensing choices.[8]

Competition over patents covering a specific technology is modelled as a patent portfolio race between two firms. In this race blocking patents arise as soon as both firms are patenting

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

in the same technology. Blocked patents are potential targets for hold up and will therefore be less valuable to firms owning them. We assume that firms patent at an exogenous rate once they have mastered a technology. The time at which each firm starts patenting is uncertain and depends on that firm's R&D investments. Furthermore, dates at which patenting starts are independently distributed. The firm which wins the patent portfolio race is the firm that starts patenting first. This firm will obtain a larger set of unblocked patents than the loser of the patent portfolio race.

To resolve blocking firms license patents. We study two alternative ways to resolve the problem of blocking: ex ante and ex post licensing. Ex ante licensing contracts prevent hold up for a specific period. They cover new patents that arrive in that period. Ex post contracts resolve hold up given firms' existing patents. The value of licensing ex post decreases as the expectation of blocking and the intensity of the patent portfolio race increase. Therefore, higher expected blocking makes ex ante licensing more valuable relative to ex post licensing.

The following propositions are derived from the model:

Proposition 1

The probability of observing ex ante licensing increases as expected blocking increases.

Proposition 2

The level of R&D investments and patenting is lowest if firms license ex ante.

These propositions are testable. In section 4 we derive an empirical framework within which to implement these tests. Here we continue by setting out the model and deriving Propositions 1 and 2.

3.1 General assumptions

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

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

Figure 1 illustrates the timing of our model. Assume that the times at which the winner

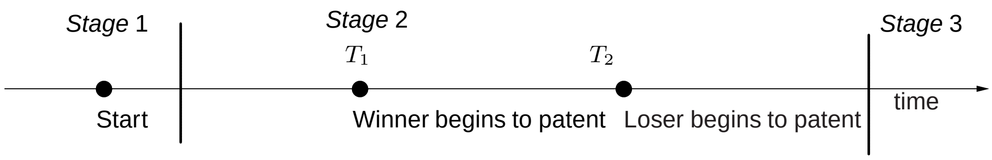


Figure 1: Time line for the patent portfolio race

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

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

All variables pertaining to winner and loser are denoted with the subscripts $_{w,l}$ below. Here h_l, h_w denote their hazard rates which capture research efforts. Note that T_1 and T_2 are independent. Then, duration of the period $T_2 - T_1$ depends on the loser's R&D investments.

We assume the period in which firms build patent portfolios in each technology is short enough that rivals' R&D efforts remain unobserved. Therefore, we adopt a model of R&D competition in which firms commit to R&D investments at the start of the game - firms have open loop strategies. Grindley and Teece (1997) argue that semiconductor firms are often ignorant of each others' research efforts which supports our assumption. Additionally, it must be borne in mind that at the USPTO patent applications were not visible until granted in the period we study. Hall et al. (2005) show that in the early 1990's patents took on average of 1.76 years to grant. Therefore, even firms watching patents granted to rivals would have learned about their research with substantial delay.

We embed the patent portfolio race into a three stage model of decisions about licensing:

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

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

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

This model is solved by backward induction.

Now consider firms profits: firms are initially symmetrical and earn profits π_0. Profits depend on the size of patent stocks to the extent that these guarantee "freedom to operate". The winner's portfolio of patents consists of unblocked patents accumulated in the period before T_2 and of patents accumulated after T_2. A proportion β of these later patents are blocked. In the absence of a licensing contract the expected sizes of winner's (Q_w) and loser's (Q_l) portfolios of unblocked patents are:[9]

$$Q_w(h_l, \beta, \lambda) = \frac{\lambda + \frac{\lambda}{r} h_l(1-\beta)}{h_l + r} \quad \text{and} \quad Q_l(h_l, \beta, \lambda) = \frac{\frac{\lambda}{r} h_l(1-\beta)}{h_l + r} \quad . \tag{1}$$

λ denotes the exogenous rate of patenting and r is the interest rate. h_l denotes the loser's research efforts. High research effort allows the loser to reduce the winner's advantage, inducing greater ex post symmetry between firms' patent portfolios.

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

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

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

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

This assumption implies that each firm's marginal benefit from additional patents is increasing in the size of their rival's patent portfolio. In patent portfolio races the relative size of firms' patent portfolios determines bargaining strength. Our assumption captures the fact that additional patents are increasingly valuable as rivals' patent portfolios grow. A simple example of a profit function which fulfils assumptions (P) and (S) is: $\pi_i = \log(Q_i) - \log(Q_i + Q_j)$.

We introduce standard restrictions on firms' R&D cost functions:

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

This implies: (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.

[9] These expressions are derived by noting that the winner will patent at rate λ before and after T_2. Then their expected patent portfolio can be written as: $\int_{s=0}^{\infty} \lambda e^{-h_l s} e^{-rs} + \frac{\lambda}{r}(1-\beta) h_l e^{-h_l s} e^{-rs} ds$. The derivation of Q_l is analogous.

We solve this model using backward induction.

3.2 Ex post licensing

An ex post licensing contract removes the threat of hold up and provides firms with "freedom to operate". Then $\beta = 0$ and patent portfolios under the ex post contract are:[10]

$$\bar{Q}_w(\lambda) = \frac{\lambda}{r} = Q_w(h_l, 0, \lambda) \quad \text{and} \quad \bar{Q}_l(h_l, \lambda) = \frac{\lambda}{r}\frac{h_l}{h_l + r} = Q_l(h_l, 0, \lambda) \quad . \tag{2}$$

$\bar{Q}$ represents the upper bound of each firm's possible patent stock which is attained when blocking is zero. We assume that the licensing contract signed by the firms conforms to the Nash bargaining assumptions. This implies the party which has a stronger bargaining position receives some of the surplus generated by the licensing contract in the form of a payment. Grindley and Teece (1997) confirm the existence of such payments as do our data. Under Nash bargaining the winner's and loser's payoffs are:

$$v_w = \frac{1}{2}\triangle\pi + \frac{1}{2}\left[\pi(\bar{Q}_w, \bar{Q}_l) + \pi(\bar{Q}_l, \bar{Q}_w)\right] \qquad v_l = -\frac{1}{2}\triangle\pi + \frac{1}{2}\left[\pi(\bar{Q}_w, \bar{Q}_l) + \pi(\bar{Q}_l, \bar{Q}_w)\right] \quad , \tag{3}$$

where the winner's expected profits are $\pi(_w, Q_l)$ and the loser's $\pi(Q_l, Q_w)$ and we 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 $v_w - v_l = \pi(Q_w, Q_l) - \pi(Q_l, Q_w)$.

The value function describing the expected return from a patent portfolio race is:[11]

$$V_p(\beta, \pi_0, h_p, H_p) = \frac{\frac{v_w(H_p,\beta)}{r}h_p + \frac{v_l(h_p,\beta)}{r}H_p + \pi_0 - \gamma(h_p)}{h_p + H_p + r}, \tag{4}$$

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

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

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

firms' research efforts. In particular the expected value of winning the patent portfolio race is declining in the loser's hazard rate H_p. The expected value of losing is increasing in the firm's own hazard rate h_p.

R&D investment

The optimal hazard rate under ex post licensing is chosen as the solution to the following optimisation problem:

$$\max_{h_p \geq 0} V_p(\beta, \pi_0, h_p, H_p) \qquad . \tag{5}$$

It can be shown that:

Proposition 3

The patent portfolio race defined by (5) is a smooth supermodular game.

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

$$\frac{\partial V_p}{\partial h_p} = \frac{1}{(h_p + H_p + r)^2} \left[\underbrace{\frac{(v_w - v_l)}{r} H_p}_{\text{Comp. threat}} + \underbrace{[v_w - \pi_0]}_{\text{Profit inc.}} + \underbrace{\frac{\partial v_l}{\partial h_p} \frac{H_p}{r} (h_p + H_p + r)}_{\text{Symmetry inc.}} \right.$$
$$\left. + \gamma(h_p) - \gamma'(h_p) [h_p + H_p + r] \right] = 0. \tag{6}$$

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

$$\frac{\partial^2 V_p}{\partial h_p \partial H_p} = \frac{1}{(h_p + H_p + r)^2} \left[\frac{(v_w - v_l)}{r} + \frac{\partial v_l}{\partial h_p} \frac{1}{r} (h_p + 2H_p + r) + \frac{\partial v_w}{\partial H_p} \frac{1}{r} (H_p + r) - \gamma'(h_p) \right] \quad , \tag{7}$$

Inserting the first order condition (6) we find the cross-partial is positive:

$$\frac{\partial^2 V_p}{\partial h_p \partial H_p} = \frac{1}{(h_p + H_p + r)^2}\left[V_p - \frac{v_l}{r} + \frac{\partial v_l}{\partial h_p}(h_p + H_p + r) + \frac{\partial v_w}{\partial H_p}\frac{1}{r}(H_p + r)\right] > 0 \quad . \tag{8}$$

We insert V_p as defined in equation (4). Consider the term in brackets: the difference of the first two terms must be positive otherwise R&D investment would not pay off. We show next that the sum of the remaining terms is also positive. Given the definitions of v_w and v_l (3) it is easily shown that their sum is increasing in firms' R&D efforts (h_p). Therefore, if the symmetry incentive is positive, so is (8). The symmetry incentive is:

$$\begin{aligned}\frac{\partial v_l}{\partial h_p} = \frac{\lambda}{2(h_p + r)^2}\Big[&\frac{\partial \pi(Q_l, Q_w)}{\partial Q_l}\beta - \frac{\partial \pi(Q_l, Q_w)}{\partial Q_w}(1-\beta) + \frac{\partial \pi(Q_w, Q_l)}{\partial Q_w}(1-\beta) \\ &- \frac{\partial \pi(Q_w, Q_l)}{\partial Q_l}\beta + \frac{\partial \pi(\bar{Q}_l, \bar{Q}_w)}{\partial \bar{Q}_l} + \frac{\partial \pi(\bar{Q}_w, \bar{Q}_l)}{\partial \bar{Q}_l}\Big] > 0 \quad .\end{aligned} \tag{9}$$

This expression is positive. To see this note that in the absence of blocking $v_l = \pi(\bar{Q}_l, \bar{Q}_w)/r$. Greater R&D effort ($h_p$) increases the size of the loser's patent portfolio Q_l and their expected profits. Therefore, (9) is positive when there is no blocking. Supermodularity of the profit function and assumption (P) imply that greater blocking increases the marginal value of R&D investment to the loser. We show this below in equation (14). R&D investment brings forward the date at which the loser begins to patent and enhances their bargaining position. Therefore, the expression is positive for all values of β.[12] We have now shown that the symmetry incentive is positive. Therefore, the cross-partial derivative is positive and the game is smooth supermodular [Milgrom and Roberts (1990)].

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

Proposition 4

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

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

Define $\hat{h}_p$ as the symmetric equilibrium solution to firms' optimisation problem (5). Then, the expected value of ex post licensing in equilibrium (4) is:

$$V_p(\hat{h}_p) = \frac{\frac{v_w+v_l}{r}\hat{h}_p + \pi_0 - \gamma(\hat{h}_p)}{2\hat{h}_p + r} \quad . \tag{10}$$

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

$$\frac{\partial V_p(\hat{h}_p)}{\partial \beta} = \frac{\partial V_p}{\partial \hat{h}_p}\frac{\partial \hat{h}_p}{\partial \beta} = -\frac{1}{2\hat{h}_p + r}\left[V_p - \frac{v_l}{r} + \left(\frac{\partial v_l}{\partial \hat{h}_p} - \frac{\partial \pi(\bar{Q}_l, \bar{Q}_w)}{\partial \hat{h}_p} + \frac{\partial \pi(\bar{Q}_w, \bar{Q}_l)}{\partial \hat{h}_p}\right)\frac{\hat{h}_p}{r}\right]\frac{\partial \hat{h}_p}{\partial \beta} \quad , \tag{11}$$

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

The expected value of ex post licensing is decreasing in the level of equilibrium R&D efforts. To see this consider once more the case in which there is no blocking. Then it may be shown that the sum of derivative terms in equation (11) is $-\partial\pi(\bar{Q}_w, \bar{Q}_l)/\partial h_p > 0$. We show below that increased blocking raises the marginal returns to R&D efforts for the loser, so that the sum of derivative terms in this equation is positive for all values of blocking.

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

Given assumptions (S) and (P) we can show that:

Proposition 5

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

To see this consider the cross-partial derivative with respect to blocking:

$$\frac{\partial^2 V_p}{\partial \hat{h}\partial \beta} = \frac{1}{(2\hat{h} + r)}\left[\frac{\partial \triangle\pi}{\partial \beta}\frac{(\hat{h} + r)}{(2\hat{h} + r)} + \frac{\partial^2 v_l}{\partial h_p \partial \beta}\frac{\hat{h}_p}{r}\right] \quad . \tag{12}$$

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

$$\frac{\partial \triangle \pi}{\partial \beta} = -\frac{\lambda}{2r}\frac{\hat{h}_p}{\hat{h}_p + r}\Big[\underbrace{\frac{\partial \pi(Q_w, Q_l)}{\partial Q_w} + \frac{\partial \pi(Q_w, Q_l)}{\partial Q_l} - \frac{\partial \pi(Q_l, Q_w)}{\partial Q_l} - \frac{\partial \pi(Q_l, Q_w)}{\partial Q_w}}_{\nu}\Big] \tag{13}$$

$$\frac{\partial^2 v_l}{\partial h_p \partial \beta} = \frac{\lambda}{2(h_p + r)^2}\Big[\underbrace{\frac{\partial \pi(Q_l, Q_w)}{\partial Q_l} + \frac{\partial \pi(Q_l, Q_w)}{\partial Q_w} - \frac{\partial \pi(Q_w, Q_l)}{\partial Q_w} - \frac{\partial \pi(Q_w, Q_l)}{\partial Q_l}}_{-\nu}\Big] \tag{14}$$

$$-\frac{\lambda^2}{2r(h_p + r)^3}\Bigg[\underbrace{\frac{\partial^2 \pi(Q_l, Q_w)}{\partial {Q_l}^2}\beta - \frac{\partial^2 \pi(Q_l, Q_w)}{\partial {Q_w}^2}(1-\beta) + \frac{\partial^2 \pi(Q_w, Q_l)}{\partial {Q_w}^2}(1-\beta) - \frac{\partial^2 \pi(Q_w, Q_l)}{\partial {Q_l}^2}\beta}_{\omega}$$
$$\underbrace{-\frac{\partial^2 \pi(Q_l, Q_w)}{\partial Q_w \partial Q_l}(1-2\beta) + \frac{\partial^2 \pi(Q_w, Q_l)}{\partial Q_w \partial Q_l}(1-2\beta)}_{\zeta}\Bigg]$$

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

Propositions 4 and 5 together lead to Proposition 1. To see this note that these propositions imply that more blocking lowers the expected value of ex post licensing (V_p). As we have shown greater blocking induces greater R&D efforts and these reduce the value of ex post licensing. Without further analysis of ex ante licensing we can infer that increases in blocking reduce the value of ex post licensing relative to ex ante licensing. To see this note that ex ante licensing by definition consists of a contract that prevents blocking. Therefore, variation in blocking has no effects on the value of ex ante licensing. In the following section we derive additional results about ex ante licensing.

3.3 Ex ante licensing

Under an ex ante licensing contract firms agree not to hold up the rival, i.e. there is no blocking. Therefore, the expected size of the firms' patent portfolios are $\bar{Q}_w$ and $\bar{Q}_l$.

Then, the analysis of firms' R&D incentives under ex ante licensing is analogous to that of ex post licensing. The value function firms maximise is:

$$V_a(0, \pi_0, h_a, H_a) = \frac{\frac{v_w(H_a,0)}{r} h_a + \frac{v_l(h_a,0)}{r} H_a + \pi_0 - \gamma(h_a)}{h_a + H_a + r} \quad . \tag{15}$$

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

$$\frac{\partial V_a}{\partial h_a} = \frac{1}{(h_a + H_a + r)^2} \Bigg[\underbrace{\frac{(v_w - v_l)}{r} H_a}_{\text{Comp. threat}} + \underbrace{[v_w - \pi_0]}_{\text{Profit inc.}} + \underbrace{\frac{\partial \pi(\bar{Q}_l, \bar{Q}_w)}{\partial h_a} \frac{H_a}{r} (h_a + H_a + r)}_{\text{Symmetry inc.}} \\ + \gamma(h_a) - \gamma'(h_a) \left[h_a + H_a + r \right] \Bigg] = 0 \quad . \tag{16}$$

Finally, it is clear that the R&D investment game firms play under an ex ante contract is also smooth supermodular. Equation (16), shows that ex ante licensing is just a form of ex post licensing in which there is no threat of blocking. Then, Proposition 2 follows from Proposition 5 as blocking is lowest under ex ante licensing.

This result does not arise from underinvestment which is usually associated with R&D cooperation. Note that we do not consider technology transfer here. Rather, as Proposition 5 shows, increases in blocking have the effect of strengthening firms' R&D incentives under ex post licensing. By implication R&D incentives under ex ante licensing are weaker than those under ex post licensing which leads to lower levels of patenting.

This model shows how the expectation of blocking affects firms' licensing behaviour. In the following section we derive an empirical model to test Propositions 1 and 2.

4 The empirical model: derivation and implementation

In this section we develop an empirical model with which to test our predictions about effects of blocking on the choice of licensing contract and patenting activity. We discuss variables used to estimate the model and provide descriptive statistics. Finally, we derive the econometric specification of our model and consider issues that arise in estimation.

4.1 A sample selection model of ex ante and ex post licensing

Our theoretical model contains three decisions: the decision to license ex ante, the decision about R&D investments and the decision to license ex post. The model shows that the expected degree of blocking determines how firms decide whether to license ex ante and how heavily they invest in R&D. If firms do not choose ex ante licensing the realization of blocking may force them to license ex post. When the realization of blocking is very low costs of licensing do not outweigh its benefits and firms do not license at all. Figure 2 below sets out the sequence of decisions taken about licensing.

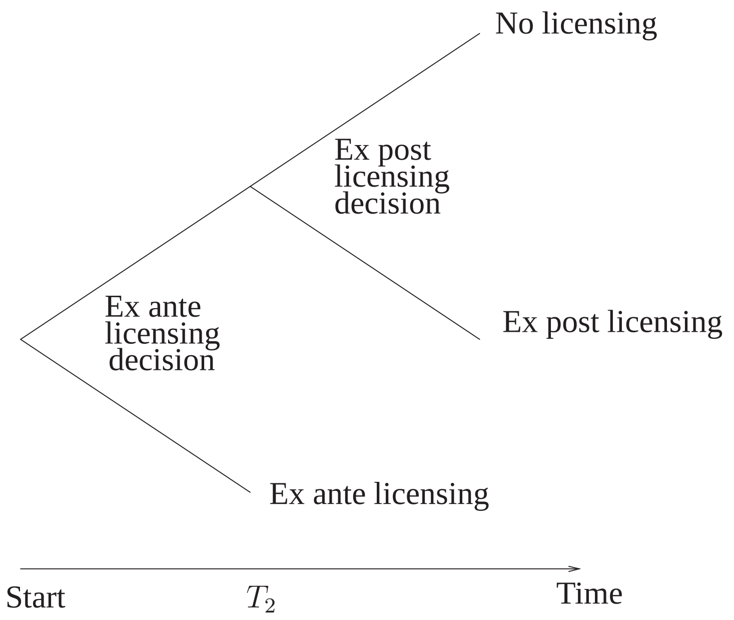


Figure 2: Structure of our empirical model

Figure 2 depicts the selection process in which firms may self select into the ex post licensing decision. It consists of the ex ante licensing decision and the ex post licensing decision. In the ex ante licensing decision firms' expectations of blocking by another firm determine whether a license with that firm is signed. If not the subsequent realization of blocking may force firms to sign an ex post license.

We use a sample selection model to capture this sequential decision process. The selection equation explains when firms select ex ante licensing. It is estimated jointly with an outcome equation modelling the choice between ex post licensing and no licensing.

The ex ante licensing decision

Firms will license ex ante if this is expected to be more valuable than not licensing ex ante. The value of not licensing ex ante is a function of the expectation of blocking and also depends on the expected transactions costs of licensing ex post. The expectation of blocking identifies the selection equation as the realization of blocking determines the decision about ex post licensing. Additionally, we can derive identification from a count variable which measures firms' previous experience of ex ante licensing. This variable is a proxy for firms' costs of ex ante licensing which do not affect the decision whether to license ex post or not. The selection equation of our model may be derived as follows:

$$\begin{aligned} \text{prob}(\Pi_a = 1) &= \text{prob}(V_a - V_p + T_a - T_p + \epsilon_a - \epsilon_p > 0) \\ &= \text{prob}(V_a - V_p + T_a - T_p > \epsilon_p - \epsilon_a) \\ &= \Phi(V_a - V_p + T_a - T_p), \end{aligned} \tag{17}$$

where T_a, T_p are transactions costs associated with ex ante and ex post licensing. ϵ_a, ϵ_p capture random variation in adoption of ex ante and ex post licensing and are assumed to be normally distributed.

This specification for the selection equation of our model provides a testable restriction if we assume that transactions costs are decreasing in licensing experience:

Hypothesis 1

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

The difference between the expected value of ex ante (V_a) and ex post licensing (V_p) is a function of the expected degree of blocking in our model. If expected blocking is zero then $V_a - V_p = 0$ and firms will not license ex ante as the costs of licensing may be avoided with very high probability. When the expectation of blocking increases the expected value of ex post licensing decreases (Propositions 4 and 5) and firms are increasingly inclined to license ex ante. The relationship between the expected value of ex post licensing and expected blocking is nonlinear (cf. equation (10)), therefore we cannot derive a structural expression for $(V_a - V_p)$. Additionally, it is clear that the expected values of ex ante and ex post licensing may depend on the levels of firms' ex ante profits (π_0), the size of their patent portfolios and the number of product markets firms operate in. For all of these variables the theoretical model does not yield testable sign restrictions. Nonetheless, they are likely determinants of firms' licensing choices and we include them in our model. The resulting specification for the selection equation of our model is:

$$\begin{aligned}\Pi_a^* =& V_a - V_p + T_a - T_p + \epsilon_\triangle \\ =& \beta_a^c + \beta_a^{EB} EB + \boldsymbol{\beta}_a^{PM} \boldsymbol{PM} + \boldsymbol{\beta}_a^{PS} \boldsymbol{PS} + \beta_a^{LA} L_A + \beta_a^{LP} L_P + \epsilon_\triangle \ ,\end{aligned} \tag{18}$$

where EB is our measure of expected blocking in a firm pair, $\boldsymbol{PM}$ is a vector of measures capturing firms' product market size, $\boldsymbol{PS}$ is a vector of measures capturing the size of firms' patent stocks and L_A, L_P count the number of previous ex ante and ex post contracts both firms were involved in. Since we do not observe the transactions costs associated with ex ante and ex post licensing directly we proxy these with firms' experience with both types of licensing as measured by L_A and L_P. $\epsilon_\triangle = \epsilon_p - \epsilon_a$ is assumed to have a variance of unity and is normally distributed.

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

Hypothesis 2

$\beta_a^{EB} > 0.$

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

The ex post licensing decision

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

The model outlined in Section 3 shows that conditional on firms' R&D expenditure the value of ex post licensing to both firms is $v_w + v_l$. Define the value of not licensing $v_n \equiv \pi(Q_w, Q_l) + \pi(Q_l, Q_w)$. Then the probability of observing ex post licensing is:

$$\begin{aligned}\text{prob}(\Pi_p = 1) &= \text{prob}(v_w + v_l - v_n - T_p + \eta_p - \eta_n > 0) \\ &= \text{prob}(v_w + v_l - v_n - T_p > \eta_n - \eta_p) \\ &= \Phi(v_w + v_l - v_n - T_p),\end{aligned} \tag{19}$$

where η_n, η_p are distributed normally. These terms capture random components of the expected value of not licensing and licensing ex post. This specification yields an additional testable restriction:

Hypothesis 3

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

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

$$\Pi_p^* = v_w + v_l - v_n - T_p + \eta_\triangle = \beta_p^c + \beta_p^B B + \boldsymbol{\beta}_p^{PM} \boldsymbol{PM} + \boldsymbol{\beta}_p^{PS} \boldsymbol{PS} + \beta_p^{LP} L_P + \eta_\triangle \ , \tag{20}$$

where B measures the realization of blocking and all other variables are defined as above. $\eta_\triangle = \eta_n - \eta_p$ is assumed to have a variance of unity and is normally distributed.

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

Hypothesis 4

$\beta_p^B > 0$.

4.2 Definition of variables and descriptive statistics

In this section we describe variables employed in our model. The data used to construct these variables are described in Appendix A. All variables characterise pairs of licensing firms. Variables are computed as the average or differences of the individual firms' characteristics where appropriate. Descriptive information for all variables is provided in Table 3. Here we also discuss variables which do not appear in the sample selection model but are used in an additional test of our model below.

The dependent variables - Π_a, Π_p, A

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

Blocking - B, EB

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

Technological similarity is measured as the uncentered correlation coefficient of the two firm's patent applications in a given year across nine patent classes [13], to which all semiconductor patents may be assigned. The definition of this measure is:

$$S = \frac{\sum_{c=1}^{9} A^{ic} A^{jc}}{\sqrt{\sum_{c=1}^{9} A^{ic}}\sqrt{\sum_{c=1}^{9} A^{jc}}} \, , \tag{21}$$

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

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

$$C^{ij} = \frac{c^{ij}}{\sum_k c^{ik}} \tag{22}$$

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

$$B = \left(C^{ij} + C^{ji}\right) S \, . \tag{23}$$

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

Firms' expectations of blocking determine whether they license ex ante. We do not observe firms' expectations of blocking. Therefore, we measure expectations of blocking with the realization of blocking in the previous period if firms do not license ex ante. Where firms chose to license ex ante we measure expected blocking using contemporaneous blocking. In

[13] These patent classes are identified by Hall et al. (2001) as the classes $257, \ 326, \ 438, \ 505$ (semiconductors), $360, \ 365, \ 369, \ 711$ (memory) and 714 (microcomponents).

doing so we assume that firms' best predictions of blocking are past observations of blocking and that the lag between ex ante and ex post decisions is a year. Table 3 shows on average this measure of expected blocking is higher under ex ante licensing than under no licensing. However, it is even higher on average under ex post licensing.

Product market competition - PM

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

Average market share We use the average market share of each firm pair in semiconductor product markets to control for the importance of the firm pair within the semiconductor industry. Larger firms are more likely to have production facilities and are therefore more susceptible to hold up than firms that do not have such facilities [Hall and Ziedonis (2001)]. Also Stuart (1998) shows that firms with more prestige within the semiconductor industry are more likely to form alliances.[14] 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 firms pairs that do not.

Difference of market shares This variable measures asymmetries in the size of firms in each pair. Differences in firm size may reduce the propensity of firms to enter into licensing contracts if size proxies the prestige of each firm in a pair [Stuart (1998)]. The descriptive statistics show the average difference in market shares was similar for licensing and non-licensing pairs.

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

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

Patent stocks - PS

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

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

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

Fragmentation Ziedonis (2004) shows 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 as firms' propensity to enter into licensing contracts could decrease if the number of firms that might hold them up increases. We apply the correction suggested in the appendix of Hall et al. (2001) to control for bias resulting from low counts. Table 3 shows on average fragmentation is greater for firm pairs that engage in licensing.[15]

Transaction costs

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

4.3 Model specification and estimation

Using these variables we estimate a sample selection model and a treatment effects model. Here we comment on the specification of the sample selection model and discuss how we constructed the sample of firm pairs to which the model is applied.

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

Table 3: Sample statistics for firm-pairs by outcome and in total

Variable		Ex ante licensing Mean	Ex post licensing Mean	No licensing Mean	Full sample Mean	Std. dev.	Min.	Max.
Ex ante licensing	Π_a	1	0	0	0.007	-	0	1
Ex post licensing	Π_p	0	1	0	0.008	-	0	1
Patent applications	A	128.452	126.002	97.662	98.105	91.824	0	790
Expected blocking	EB	0.007	0.009	0.004	0.004	0.009	0	0.369
Blocking	B	0.007	0.011	0.005	0.005	0.010	0	0.216
Average patent stock	PS	530.876	474.633	371.256	373.198	424.330	0	4968
Difference in patent stocks	PS	632.016	542.755	483.115	484.627	570.965	0	5630
Fragmentation	PS	0.818	0.874	0.672	0.675	0.844	0	1.992
Average market shares	PM	0.030	0.030	0.024	0.024	0.019	0	0.108
Difference in market shares	PM	0.030	0.027	0.030	0.030	0.026	0	0.164
Multimarket participation	PM	1.640	1.599	1.509	1.511	0.512	1	3
Previous ex post contracts	L_A	6.702	7.925	6.090	6.110	6.896	0	51
Previous ex ante contracts	L_P	9.538	7.350	6.949	6.970	5.825	0	37
1990		0.080	0.136	0.081	0.081	-	0	1
1991		0.184	0.139	0.176	0.176	-	0	1
1992		0.188	0.286	0.267	0.266	-	0	1
1993		0.116	0.041	0.126	0.126	-	0	1
1994		0.128	0.136	0.154	0.153	-	0	1
1995		0.072	0.085	0.073	0.073	-	0	1
1996		0.096	0.024	0.018	0.018	-	0	1
1997		0.068	0.037	0.036	0.036	-	0	1
1998		0.028	0.024	0.023	0.023	-	0	1
Observations		250	294	35,731	36,225			

The sample selection model The model takes the following form:

$$\Pi_a^* = \alpha_a + \beta_a^{EB} EB + \boldsymbol{\beta}_a^{PM} \boldsymbol{PM} + \boldsymbol{\beta}_a^{PS} \boldsymbol{PS} + \beta^{LA} L_A + \beta^{LP} L_P + \epsilon_\triangle \tag{24}$$

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

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

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

The sample To estimate the model we construct a sample of all firm pairs in the semiconductor industry. We use all firms that had positive market shares in the semiconductor industry between 1989 and 1999 in this sample. This leads to a cross section with $36,225$ observations. Out of these we observe 294 ex post licensing and 250 ex ante licensing contracts. The number of ex ante and ex post contracts in this sample is a subset of the licensing contracts we describe in section 2. This happens because we restrict our sample to firms with positive market shares in the semiconductor industry.

5 Results

In this section we present results from the sample selection model presented in section 4. We test exclusion restrictions derived from theory and restrictions suggested by our results. Then, we derive a treatment effects model and present results for it. This model provides an additional test of the patent portfolio race model. Finally, empirical results are discussed.

5.1 Effects of blocking on licensing

Which factors determine whether a firm pair license ex ante? When do firms that avoided ex ante licensing contract ex post? We predict higher expected blocking and experience of ex ante licensing raise the probability of observing ex ante licensing. Also, higher realized blocking raises the probability of observing ex post licensing. To test these predictions a sample selection model is estimated (24). Table 4 provides results of two specifications for the sample selection model. Table 5 sets out marginal effects for our preferred specification.

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

Table 4 provides two alternative specifications of the sample selection model. In columns (2) and (3) we report a model that includes the expectation of blocking as an additional control variable in the outcome equation of the sample selection model. Columns (4) and (5) report the same model without expected blocking in the outcome equation.

Table 4: Coefficients for sample selection models of licensing

	Bivariate probit		Bivariate probit	
	Pr(Ex post)	Pr(Ex ante)	Pr(Ex post)	Pr(Ex ante)
Independent Variable	(2)	(3)	(4)	(5)
Blocking	9.802***		11.812***	
	(2.483)		(1.661)	
Expected blocking	3.549	6.612**		5.581*
	(3.174)	(3.047)		(2.909)
Average patent stock		-0.000**		-0.000**
		(0.000)		(0.000)
Differences in patent stocks	0.000*	0.000	0.000**	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Fragmentation	-0.061*	-0.097**	-0.051*	-0.088**
	(0.032)	(0.044)	(0.031)	(0.043)
Average market shares	7.956***	4.665**	8.068***	4.737***
	(1.335)	(1.844)	(1.330)	(1.841)
Differences in market shares	-5.594***	-3.456***	-5.647***	-3.477***
	(0.940)	(1.179)	(0.940)	(1.180)
Multimarket participation	-0.017*	0.042	-0.018	0.041
	(0.049)	(0.063)	(0.049)	(0.063)
Previous ex post contracts		-0.017***		-0.018***
		(0.004)		(0.004)
Previous ex ante contracts		0.052***		0.052***
		(0.009)		(0.009)
Year dummies	YES	YES	YES	YES
Constant	-2.336***	-2.862***	-2.324***	-2.854***
	(0.115)	(0.159)	(0.115)	(0.159)
ρ	-0.9755***		-0.9750***	
	(0.0175)		(0.02)	
$-\ln L$	2613.175		-2613.799	

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

Based on our theoretical model we predict that expected blocking acts as an exclusion restriction providing identification for the sample selection model. The presence of additional exclusion restrictions in the model allow us to test the validity of this prediction. Column (2) of Table 4 shows expected blocking is not significant in the outcome equation of the sample selection model. A likelihood ratio test comparing the two bivariate probit models reveals that expected blocking is a valid exclusion restriction ($\chi^2(1) = 1.25$). Therefore, we prefer the model presented in columns (4) and (5). Evidence of sample selection is strong in both models as the correlation coefficient ρ is significant and negative.

We test our preferred model against several further specifications: (i) we include previous ex post licensing in the outcome equation ($\chi^2(1) = 0.57$) and we also include both previous ex post and ex ante licensing in the outcome equation ($\chi^2(1) = -5.73$). In both cases we can clearly reject these alternative specifications. Therefore, Hypothesis 3 is not confirmed in our dataset: costs of licensing ex post are insignificant in the ex post licensing decision. In contrast, Hypothesis 1 states that experience with ex ante (ex post) licensing will increase (reduce) the probability of ex ante licensing. This hypothesis is confirmed: coefficients and marginal effects on these variables are highly significant in the selection equation (5).

More importantly Hypothesis 2 is confirmed. Table 5 shows that the marginal effect of expected blocking is significant at the 5% level. Also Hypothesis 4 is confirmed: realized blocking raises the probability of ex post licensing very significantly. These findings show that blocking patents determine licensing as we predict lending support to our theoretical model of patent portfolio races.

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

How important are these factors in determining licensing? The conditional probability of observing ex ante licensing based on our preferred model is quite low: 0.0053. The conditional probability of ex post licensing is 0.0065. These low probabilities result from the large number of firm pairs in the semiconductor industry which do not license. A one standard deviation increase in the expectation of blocking raises the probability of observing ex ante licensing by 0.0009 at the mean. This is an increase of 17% in the probability of ex ante licensing. A one standard deviation increase in market shares of a firm pair raises the probability of observing ex ante licensing by 0.0011, an increase of 21%. Table 5 shows that a one standard deviation increase in symmetry of firms in a pair has a comparable effect on the probability of observing ex ante licensing: it increases by 0.001 (19%). An increase in the size of the joint patent stock of a firm pair by one standard deviation reduces the probability of observing ex ante licensing by 0.0012 (21%). All of these effects are substantial. Turning to the fragmentation of firms patent citations we observe that this variable increased by over

0.4 over the sample period. This corresponds to a decreased probability of observing ex ante licensing of 10%. Finally, additional experience of one previous ex ante contract increases the probability of observing ex ante licensing by 16% while previous experience of ex post licensing reduces it by 5%.

Table 5: Marginal effects for the bivariate sample selection model of licensing

Independent Variable	Bivariate probit Pr(Ex post) (1)	 Pr(Ex ante) (2)
Blocking	0.240***	
	(0.037)	
Expected blocking		0.102**
		(0.048)
Average patent stock		-0.000
		(0.000)
Differences in patent stock	0.000**	0.000
	(0.000)	(0.000)
Fragmentation	-0.000	-0.001**
	(0.001)	(0.001)
Average market shares	0.162***	0.060**
	(0.032)	(0.029)
Differences in market shares	-0.128***	-0.040**
	(0.021)	(0.019)
Multimarket participation	-0.001	0.001
	(0.001)	(0.001)
Previous ex post contracts	0.000**	-0.000***
	(0.000)	(0.000)
Previous ex ante contracts	-0.000**	0.001***
	(0.000)	(0.000)

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

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

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

The probability of observing ex post licensing rises by 0.0024 (36%) if blocking increases by one standard deviation at the mean. An increase in market shares by one standard deviation raises the probability of ex post licensing by 0.0030 (47%). Increasing symmetry of market shares by one standard deviation raises this probability by 0.0033 (51%).

These effects are larger than those reported for the ex ante licensing decision. Ex post licensing is an important mechanism for firm pairs that have not licensed ex ante but find that they block each others patents to a significant degree. Especially larger and more symmetrical firm pairs resolve this problem by licensing ex post. Increasing fragmentation of patent citations has no significant marginal effects on the ex post licensing decision, although the sign of the coefficient indicates that ex post licensing is less likely as fragmentation increases.

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

5.2 Effects of licensing on patenting

Proposition 2 indicates that firms' R&D investments will be higher under ex post licensing than under ex ante licensing. In this section we derive a treatment effects model to test this proposition.[16]

Derivation of a treatment effects model

The treatment effects model allows us to treat the decision to license ex ante as an endogenous binary variable in an ordinary least squares regression explaining the level of patenting by a firm pair. Just like the sample selection model the treatment effects model consists of two stages. We use the selection equation (18) of the sample selection model to explain ex ante licensing. This equation is jointly estimated with an outcome equation explaining the level of patenting in the firm pair.

[16] This model is also referred to as a switching regression model with endogenous switching by Maddala (1983).

Firms decide on the level of patent applications independently. Our empirical specification for the treatment model preserves the logic of modelling the behaviour of firm pairs to make it comparable to the sample selection model. The dependent variable in the outcome equation of the treatment effects model is the sum of patent applications in each firm pair. The sum of applications is lower if firms in a pair formed an ex ante licensing contract. Accordingly, the firms' joint level of patent applications A is determined as follows:

$$A = \beta_{ot}^{c} + \beta_{ot}^{D}\Pi_a + \beta_{ot}^{B}B + \boldsymbol{\beta}_{ot}^{PM}\boldsymbol{PM} + \boldsymbol{\beta}_{ot}^{PS}\boldsymbol{PS} + \beta_{ot}^{LP}L_P + \nu \quad , \tag{25}$$

where Π_a is the endogenous dummy variable capturing whether firms have licensed ex ante or not. All other variables are defined as previously. Identification of the treatment effects model results from the same exclusion restrictions as in the sample selection model as Π_a is determined as set out in the sample selection model (24). The treatment effects model is:

$$\begin{aligned} \Pi_a^* &= \beta_a^c + \beta_a^{EB}EB + \boldsymbol{\beta}_a^{PM}\boldsymbol{PM} + \boldsymbol{\beta}_a^{PS}\boldsymbol{PS} + \beta_a^{LA}L_A + \beta_p^{LP}L_P + \epsilon_\triangle \\ A &= \beta_{ot}^{c} + \beta_{ot}^{D}\Pi_a + \beta_{ot}^{B}B + \boldsymbol{\beta}_{ot}^{PM}\boldsymbol{PM} + \boldsymbol{\beta}_{ot}^{PS}\boldsymbol{PS} + \beta_{ot}^{LP}L_P + \nu \\ \Pi_s &= \begin{cases} 1 & \text{if} \quad \Pi_a^* > 0 \\ 0 & \text{if} \quad \Pi_a^* \leq 0 \end{cases} . \end{aligned} \tag{26}$$

This model is estimated by FIML.

Results from the treatment effects model

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

A comparison of results in these tables shows that the selection equations deliver similar results. We cannot reject the hypothesis that the coefficients for corresponding variables in the two models are statistically identical. This further confirms the robustness of our modelling approach.

The outcome equation (Column (1) in Table 6) of the treatment effects model describes the joint level of patenting in a firm pair. We find that ex ante licensing has a significant negative effect on the patenting levels adopted by firms which contract ex ante. Such a contract reduces the size of the joint patent portfolio by 12.5 patents, a 13% reduction in the level of patenting. This result confirms the prediction of Proposition 2 and lends further support to the theoretical model of patent portfolio races derived above.

Table 6: Coefficients and marginal effects for the treatment effects model of patent applications

	Coefficients		Marginal effects
Independent Variable	Patent applications (1)	Pr(Ex ante) (2)	Pr(Ex ante) (3)
Ex ante licensing dummy	-12.551**		
	(4.323)		
Blocking	-435.949***		
	(24.596)		
Expected blocking		6.696*	0.101*
		(3.104)	(0.047)
Average patent stocks	0.194***	-0.000*	-0.000
	(0.001)	(0.000)	(0.000)
Differences in patent stocks	0.008***	0.000	0.000
	(0.001)	(0.000)	(0.000)
Fragmentation	16.137***	-0.100*	-0.002*
	(0.328)	(0.045)	(0.001)
Average market shares		3.391*	0.051*
		(1.869)	(0.028)
Differences in market shares		-3.294***	-0.050**
		(1.222)	(0.018)
Multimarket participation	6.491***	0.048	0.001
	(0.403)	(0.065)	(0.001)
Previous ex post contracts		-0.014**	-0.000**
		(0.005)	(0.000)
Previous ex ante contracts		0.062***	0.001***
		(0.010)	(0.000)
Year dummies	YES	YES	
Constant	-84.392***	-3.055***	
	(1.303)	(0.194)	
ρ	0.126		
σ	31.98		
$-lnL$	152115.53		

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

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

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

Our findings provide an interesting contrast between effects of size in technology and product space. Firms with large shares of semiconductor product markets are highly likely to engage in licensing. This confirms the importance of licensing for competition in product markets: firms with important production facilities rely on licensing to guarantee freedom to operate [Grindley and Teece (1997)]. In contrast, the size of firms' patent portfolios affects their propensity to patent significantly while having little or no direct effect on licensing. Only differences in firms' patent stocks affects the probability of ex post licensing.

6 Conclusion

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

Our results indicate that licensing in the semiconductor industry is undertaken primarily by larger and more symmetric pairs of firms. We show that licensing choices made by such firms is consistent with a model of patent portfolio races in which licensing guarantees freedom to operate. This contrasts with existing models of licensing which focus on technology exchange and or attempts to affect the intensity of product market competition [Scotchmer (2004), Shapiro (2003a)]. We also show that licensing ex ante, before R&D investments are made allows firms to reduce the levels of patenting. This finding further supports the patent portfolio race model of patenting in the semiconductor industry.

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

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

To test our model of technology competition and licensing in the semiconductor industry we estimate two models: a bivariate probit sample selection model explaining selection into ex post licensing and a treatment effects model explaining the level of patent applications. Using both models we are able to test separate predictions of our theoretical model. We are unable to reject the main predictions of the model. Thus expected and realized blocking strongly affect firms' propensity to engage in licensing. If firms license ex ante this reduces the level of patenting significantly.

Additionally, we find that especially firms with large product market shares in the semiconductor product markets engage in licensing. These firms choose both ex ante and ex post licensing to a significantly higher degree than firms with low market shares. Asymmetry of market shares reduces the likelihood that firms engage in licensing. This also indicates that the "freedom to operate" explanation of licensing is central to understand licensing in patent thickets. Interestingly the size of firms' patent portfolios does not affect their propensity to license. However it does affect firms' patenting levels. Finally, we find that the fragmentation of patent rights reduces firms' propensity to license ex ante and ex post. Thus a deepening of patent thickets resulting from more complex blocking relationships seems to undermine the usefulness of licensing to resolve blocking.

These results imply that licensing has important pro competitive benefits in the semiconductor industry. Ex ante licensing reduces competitive pressure and the intensity of patent portfolio races if firms expect blocking to be high. As the theoretical model indicates, these are precisely the settings in which the pressure to patent is greatest. Ex post licensing allows firms at least to exchange blocking patents in settings in which patent portfolio races are less intense. Worryingly our results also indicate that licensing becomes less important as patent ownership becomes more fragmented.

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

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A Data sources

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

A.1 Licensing

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

The dataset covers licensing contracts in which at least one party has a principal line of business in the semiconductor industry between 1989-1999. All such firms for which annual semiconductor market shares were available during the period 1989-1999 were included in the sample. This sampling criterion was imposed because firms' product market positions are an important variable in our theoretical as well as statistical model. We identified name changes and subsidiaries and mergers from a variety of sources including Thomson Financial, Dataquest, and Moody's. We collect a total of 372 licensing contracts with an annual average of 34 contracts. Our data on licensing contain information on each individual contract. Details encompass the time the licensing contract was signed, the firms involved and a synopsis indicating the purpose, technology and the type of licensing, e.g. whether firms signed ex ante or ex post licensing contracts. We went through every synopsis and classified the licensing contracts into ex ante and ex post contracts. For consistency with our theoretical model our empirical analysis of licensing is restricted to horizontal technology licensing. Hence, we have excluded vertical partnerships, such as those between semiconductor firms and computer, microelectronic or multimedia firms. In line with the previous literature we classified a licensing contract as horizontal if more than 50% of the firms had sales in the semiconductor industry. We also excluded contracts that were based exclusively on production and marketing licensing. Finally, we dropped another 22 licensing contracts which were related to litigation. This left us with 579 contracts over the whole time span.

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.[17] The correspondence in the number of contracts observed confirms that our dataset

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

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 favour ex ante or ex post licensing contracts when announcing licensing contracts to the public.

A.2 Patents

In order to capture firms' positions in technology space we use information on granted patents.[18] 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 dataset established by Hall, Jaffe, and Trajtenberg (2001).[19] The database comprises detailed information on 3 million U.S. patents granted between 1963 and 1999, and all citations made between 1975 and 1999 (more than 16 million).

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

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

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

[18] 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.

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

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

A.3 Market data

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

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

B Examples for ex ante and ex post licensing

This section contains examples of licensing contracts taken from our dataset.

EX ANTE LICENSING

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

EX POST LICENSING

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