IP-for-IP or Cash-for-IP? R&D Competition and the Market for Technology*

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Abstract

This paper argues that firms use 'IP-for-IP' policies such as cross-licensing to strategically restrict transactions in the market for technology. The commitment to limit trade to reciprocal exchange (barter instead of cash transactions) enables firms to alter the allocation of R&D and soften R&D competition. In particular, it induces firms to focus R&D on their area of expertise. The costs of IP-for-IP are foregone gains from trade. Our analysis of the trade-offs involved shows that IP-for-IP is profitable in industries where firms differ in their capabilities to commercialize IP. Patent complementarities and firm asymmetries further strengthen the optimality of IP-for-IP.

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1 Introduction

What type of "currency" should firms choose when they trade intellectual property (IP)? Looking at the empirical evidence, it is not obvious that cash is the most preferable method of payment. Rather, it seems that firms pay with their own IP in exchange for other firms' technology. This is evident in the empirical discussion of so-called cross-licensing agreements. Put simply, cross-licensing implies granting reciprocal access to IP or patents by firms. Evidence suggests that cross-licensing is more than a simple, reciprocal seller-buyer-relation but is part of a long-term strategy. Intel's formerly proclaimed "IP-for-IP" strategy is a case in point. This strategy involved that Intel committed itself to grant access to its IP only to firms who gave Intel access to their own IP.[1] Hence, Intel purposely restricted its own trade of IP to non-monetary transactions. On a more general level, Cohen, Nelson, and Walsh (2000) observe that for product innovations in complex product industries, 45% of the firms use patents for blocking and negotiation reasons, but not in order to earn license revenues. They also report that "[r]espondents noted that firms are reluctant to sell their technology, but are willing to trade it only to firms that have valuable technology (intellectual property) to use as currency" (p.29).

This paper suggests that the choice of currency (cash versus IP) affects the R&D activity of firms. We show that a commitment to an IP-for-IP strategy can be a profitable means to alter the allocation of R&D investments and thus soften R&D competition. However, such a strategy involves costs as it forgoes potential gains from trade when IP is distributed asymmetrically in the market. By providing a simple model of the trade-offs involved, this paper shows that IP-for-IP has ex ante impacts on firms' innovative activities.

We consider two firms that are engaged in the same two R&D projects. This implies that each firm has to decide about its overall R&D investment as well as the allocation across projects. The projects stochastically yield IP that can be commercialized, each in a different market. However, firms differ in their ability to commercialize IP in these markets due to differences in assets complementary

[1] According to Shapiro (2002), "[t]he FTC alleged that Intel ... was acting anti-competitively by refusing to license certain trade secrets to firms that would not enter into cross-licenses with Intel." For further details refer also to Shapiro (2001), Shapiro (2004), and the FTC's documentation at http://www.ftc.gov/os/caselist/d9288.shtm.

to innovations (e.g. in sales and marketing or in subsequent manufacturing processes; see Teece, 1986, 2006). This allows them to capture gains from trade when a firm with lower commercialization ability sells its IP to the one with higher ability. At the same time, gains from trade also raise the incentives to pursue R&D in projects outside firm's key markets, thus increasing R&D competition.

By committing to an IP-for-IP strategy, firms may restrict R&D competition. This affects both the level and allocation of R&D expenditures. In particular, IP-for-IP generates a higher level of 'expertise', that is, a greater focus of R&D on firms' areas of high capability. The analysis shows that strategies of restricting trade in technologies to reciprocal exchange can be profit-enhancing. This is particularly the case in industries where firms differ in their commercialization abilities. The profitability of choosing an IP-for-IP strategy is even more pronounced (1) when patents are complements and (2) for asymmetries between firms.

There is a growing body of literature that studies the impact of technology licensing and intellectual property design on market structure and welfare. This literature in particular focuses on the effect of licensing on competition (Shapiro, 2003; Lerner and Tirole, 2004) and litigation (Choi, 2010). These analyses usually provide 'ex-post' analyses of cross-licensing, i.e. based on situations where two (or more) firms already possess patents. Cross-licensing agreements (or patent pools as an extension thereof) thus arise naturally as agreements between multiple owners of patents. While these aspects are of great importance, it appears that there is more to cross-licensing than the mere composition of two distinct licensing deals. In particular, several analyses of cross-licensing highlight the reciprocal aspect in accessing technology. For example, according to Grindley and Teece (1997, p.23), "to obtain access to needed technologies, Hewlett-Packard needs patents to trade in cross-licensing agreements. ... This IP portfolio ... is also invaluable as leverage to ensure access to outside technology." The same authors report that IBM acquires necessary outside IP rights "primarily by trading access to its own patents, a process called 'cross-licensing' " (p.15). Referring to conversations with semiconductor firms, Hall and Ziedonis (2001, p.107) argue that "many manufacturers had decided to 'harvest' more patents from their R&D ... to assist them in winning favorable terms in cross-licensing negotiations with other firms in the industry."[2] The relevance of using patents in negotiations (but not as a source of licensing revenues) is also reflected in the survey findings of Cohen, Nelson, and Walsh (2000).

Overall, these reports of cross-licensing agreements and firms' motivations to patent raise the question why a firm's own IP (cross-licensing) is a different currency than cash (one-way licensing) when seeking access to outside technology. In a more general context, Prendergast and Stole (1996) address the potential economic implications of monetary versus non-monetary trade (i.e. barter) in assets. We contribute to the literature by highlighting why the type of currency in the market for technology might matter in the context of firms' R&D activities.

Our model contains the features of a patent race and is therefore closely related to the traditional patent race literature. The symmetric models incorporated in Loury (1979) and Lee and Wilde (1980) show that patent races among a fixed number of firms lead to overinvestment in R&D compared to the cooperative solution.[3] The major reason for the existence of overinvestment is the difference between the private and the social value of a patent. However, unlike in our paper, these models are not concerned with project choice in R&D. This links our analysis to the literature focusing on project choice rather than the level of investments in R&D (e.g. Bhattacharya and Mookherjee, 1986; Dasgupta and Maskin, 1987; Cabral, 2003; Gerlach, Ronde, and Stahl, 2005; Anderson and Cabral, 2007). These papers are primarily interested in the choice of risk that firms take in R&D competition given a fixed R&D budget. In our paper we do not consider risk-taking behavior by firms. Rather, firms' allocation of R&D across investment projects is driven by the trading environment in the market for technology.

Looking at multiple research projects highlights two different motives for firms to undertake R&D. Apart from the obvious value of an innovation in its use at the inventor, an innovation may be valuable as a tradeable good (provided property rights are well specified). This latter value often features in the management literature on innovation (see Arora, Fosfuri, and Gambardella, 2001). However, the value of technology as a tradeable good depends on the benefits from and

[2]In a similar way, The Economist (2005) writes that "[u]nless firms have patents of their own to assert so they can reach a cross-licensing agreement (often with money changing hands too), they will be in trouble."

[3]For a survey on these and additional models on patent races, see Reinganum (1989).

the terms of trade. Benefits from trade arise because firms differ in capabilities regarding the commercialization of innovations. However, an IP-for-IP trading restriction limits the realization of the gains from trade and in turn alters the relative weight of firms' R&D motives. The paper shows how this changes incentives to undertake R&D across different types of projects.

The paper is organized as follows. Section 2 introduces the key assumptions of the model. Section 3 first analyzes R&D competition under free trade versus IP-for-IP and compares the outcomes of these two regimes before considering the profitability of an IP-for-IP based strategy. Section 4 introduces a more specific cost function in order to provide a more detailed analysis. Section 5 then introduces complementary patents to explicitly analyze cross-licensing agreement. This section also illustrates why even stronger trading restrictions than IP-for-IP can be less profitable. Section 6 introduces asymmetric firms. Finally, section 7 concludes.

2 Model

Set-up: We consider two firms ($i = 1, 2$) that are potentially engaged in two markets ($j = 1, 2$). In each market, a firm can pursue a research project which stochastically yields at most one patent covering its whole R&D output.[4] The maximum (market) value of either patent is symmetric and given by V. The whole R&D process is sufficiently uncertain such that the outcome is non-contractible. Hence, firms cannot write ex ante (licensing or sale) contracts for the new patent. Firms can be heterogeneous with respect to their core market. This difference is captured by two aspects: (i) Firms differ in their commercialization abilities regarding the patents. We assume that firm i can fully exploit the value of patent i whereas it can only realize a fraction $\delta \in [0, 1]$ of the value of patent $j \neq i$. (ii) Each firm has a (weak) advantage in terms of R&D cost within the market where it has full commercialization ability. This is more clearly specified in the next step.

[4]We initially rule out complementary patent relationships within a certain project. This assumption is relaxed in section 5. Moreover, patent protection is assumed to be perfect, i.e. it is not possible to invalidate a granted patent in court.

R&D Strategies and Costs: Firms decide about the unconditional probability of success in each project. If both firms are successful on a certain project then each firm obtains the respective patent with probability 1/2. Let the unconditional success probability of firm i for project j be $s_{ij} \in [0,1]$ with cost $c_i(s_i) \geq 0$, where s_i denotes the strategy tuple of firm i. We assume that the firm's cost functions are continuously differentiable and symmetric. Additionally, we assume for $i, j, k \in \{1, 2\}$ and $i \neq k$

$$\frac{\partial c_i}{\partial s_{ij}} \geq 0 \ , \ \frac{\partial^2 c_i}{\partial s_{ij}^2} \geq 0 \ , \ \frac{\partial^2 c_i}{\partial s_{ii} \partial s_{ik}} \geq 0 \tag{C1}$$

and for any $s'_{ik} > s'_{ii}$

$$c_i(s'_{ii}, s'_{ik}) \geq c_i(s'_{ik}, s'_{ii}) \ , \ \left. \frac{\partial c_i}{\partial s_{ik}} \right|_{\substack{s_{ii}=s'_{ii} \\ s_{ik}=s'_{ik}}} \geq \left. \frac{\partial c_i}{\partial s_{ii}} \right|_{\substack{s_{ii}=s'_{ik} \\ s_{ik}=s'_{ii}}} \tag{C2}$$

Assumption C1 implies that costs are increasing and (weakly) convex and that there are no benefits of scope across the two projects. C2 implies that a firm has a potential cost advantage (or: no cost disadvantage) in its core market. While these assumptions suffice to illustrate the main trade-off in the model, we will later use a specific cost function in order to derive further results .

Trade in Technology: Once firms have obtained patents they are potentially free to trade these. By doing so, firms can realize gains from trade in cases where $\delta < 1$. If trade takes place then it is assumed that firms bargain with equal bargaining power over the price of the patent to be exchanged.[5] In the model, the terms of trade in technology chosen play a crucial role. Firms may choose between two scenarios. In the first scenario, labeled "free trade", firms can exchange patents without any restrictions. This enables them to realize all gains from trade. In contrast, we consider a second scenario where firms are restricted in their trading opportunities. We refer to this case as "IP-for-IP". Under the terms of IP-for-IP, firms are not able to use money for the purchase of a patent from another firm. Rather, a firm may only use its own IP as currency for the IP

[5] The basic model only considers barter (or, put differently, exclusive licensing) and therefore neglects licensing deals which involve simultaneous usage of a patent by both firms. We examine multiple usage of patents in section 5.

of the other firm. That is, in the IP-for-IP scenario, trade in technology has to take place on a reciprocal basis. Contrary to the free trade case, with IP-for-IP firms may not be able to exploit all potential gains from trade.

Time Structure and Equilibrium Concept:

t=0 Firms simultaneously set their terms of trade.

t=1 Firms simultaneously decide about their R&D investments.

t=2 Nature determines the allocation of patents (conditional on R&D expenditures)

t=3 Trade takes place if the terms of trade of both firms allow it.[6] All payoffs are realized hereafter.

We assume that firms can commit themselves to the terms of trade set initially when they enter the trading stage. As will be clear below, firms might want to change these terms in the last stage of the game. Hence, we enable firms to restrict their ability to change their initial decision.[7]

We are looking at subgame perfect equilibria of the game in order to determine when trade restricting strategies may be part of firms' equilibrium behavior. The key part of the analysis will be to examine the decision on R&D expenditures in t=1, where we look for symmetric Nash equilibria. Additionally, in case of multiple equilibria, we disregard those equilibria that are always Pareto dominated. Finally, we define the following characterization of equilibria:

Definition

A (symmetric) equilibrium (s^*_{ii}, s^*_{ij}) *has "higher expertise" than equilibrium* (s'_{ii}, s'_{ij}) *if* $s^*_{ii} \geq s'_{ii}$ *and* $s^*_{ij} \leq s'_{ij}$ *for* $i \neq j$*. Equilibrium* (s^*_{ii}, s^*_{ij}) *is called an "expert equilibrium" if (i)* $s^*_{ii} \geq s^*_{ij}$ *for* $i \neq j$ *and (ii) it has higher expertise than any other equilibrium.*

[6] As the IP-for-IP scenario is more restrictive than the free trade scenario and since trade only occurs if both firms agree to it, the IP-for-IP scenario always applies if it is chosen by at least one firm in t=0.

[7] This might be achieved by delegating the decision in t=0 to a (central) manager who maximizes expected profits and incurs costs if he were to deviate from his initial decision. See e.g. the discussion in Maskin and Tirole (1999) about how renegotiation can be avoided. Alternatively, one may rationalize this commitment power in an infinitely repeated game.

Hence, expertise in this context is captured by the firms focusing their R&D investments more on the market where their comparative advantage (in terms of costs and commercialization ability) is than on the other market.

3 Analysis

In the following, we characterize equilibrium R&D expenditures under the free trade (FT) and the IP-for-IP (IP) scenario (section 3.1). In 3.2, we look at the choice of free trade versus IP-for-IP.

3.1 Equilibrium R&D Investments

Generally, firms' profits depend on the pre-trade allocation of patents by nature and the trading environment which determines the final allocation of a patent. Let $\omega_j \in \Omega \equiv \{\emptyset, 1, 2\}$ denote the post-R&D, *pre-trade* owner of patent j. Then there are nine possible pre-trade allocations of patents (ω_1, ω_2). Let $p(\omega_1, \omega_2)$ be the probability of an allocation. Similarly, let $\pi_i^{\Theta}(\omega_1, \omega_2)$ denote firm i's *post-trade* payoff from this allocation, which depends on the trading scenario $\Theta \in \{FT, IP\}$: When there are no restrictions to trading technology, each firm will ex post be allocated the patent it values most. The price at which patents are traded is determined by bargaining such that the parties split the gains from trade equally. Under IP-for-IP, gains from trade can only be realized if trade takes place on a reciprocal basis. The payoffs in this scenario consequently differ from the free trade payoffs in some but not all states of the world as long as firms have different commercialization abilities regarding the two patents (i.e. as long as $\delta < 1$).

[Insert Table 1 about here]

Table 1 provides the probabilities and payoffs to the two firms for all possible patent allocations and scenarios. Consider for example allocation $(\emptyset, 1)$: Firm 1 gains the patent for market 2 and values it at δV. As firm 2's valuation is higher, they trade and split the gains, $(1-\delta)V$, equally under free trade. However, under IP-for-IP, there is no possibility to barter, so firm 1 uses the patent itself at the reduced value of δV. Similarly, for allocation $(2, 2)$: Under free trade firm 2 sells the patent for market 1 to firm 1, whereas it keeps both patents under IP-for-IP.

In case of allocation $(2,1)$, the two firms exchange the patents gained in R&D under both trading scenarios, without money changing hands due to symmetric valuations.[8]

Given the above payoff structure, firm i's expected profit in the R&D stage under trading scenario Θ is

$$E[\pi_i^\Theta] = \sum_{\omega_1 \in \Omega} \sum_{\omega_2 \in \Omega} p(\omega_1, \omega_2) \pi_i^\Theta(\omega_1, \omega_2) - c(s_{ii}, s_{ij}) \ . \tag{1}$$

Under free trade the two research projects are not strategically linked with each other as trading patent 1 is not affected by the trade of patent 2. The introduction of IP-for-IP based trade restrictions strategically interlinks both research projects: The ability to trade a certain patent depends on the distribution of patents over both projects. If δ is smaller than one then a firm might be forced to commercialize a patent at value δV while trade would have been desirable. However, if the competing firm happens to have to other patent, that is for allocation (2,1), exchange is possible. We can now derive the following results for the R&D investment stage.

Lemma 1

1. *For $\delta = 1$, free trade and IP-for-IP yield the same set of equilibria.*

2. *There always exists an expert equilibrium under free trade and IP-for-IP.*

3. *For both free trade and IP-for-IP, an equilibrium (s'_{ii}, s'_{ij}) with $s'_{ij} > s'_{ii}$ and $i \neq j$ is always Pareto-dominated by another equilibrium with higher expertise.*

Proof: See A.1

The first result in Lemma 1 is trivial: For $\delta = 1$, firms are homogenous as they have identical commercialization abilities. This implies that there are no gains from trade and hence, trade or trade restrictions do not affect firm profits. The second result is more important, as it establishes existence of both, equilibrium and a partial ordering of equilibria in terms of expertise. Lastly, Lemma 1 also establishes that equilibria where firms invest more in the market where their commercialization ability is lower than in the other market are always Pareto-dominated.

[8] We consider asymmetric valuations in section 6.

The existence results of Lemma 1 are obtained by transforming the R&D investment model into a supermodular game where symmetric equilibria and order properties have been derived (see Vives, 1999, 2005). The following result also builds upon comparative statics for equilibria in supermodular games:

Proposition 1
The expert equilibrium under IP-for-IP has higher expertise than the expert equilibrium under free trade.

Proof: See A.2

This results states that the ordering of equilibria by expertise can also be applied to the expert equilibria across the two trading scenarios. It shows that choice of IP-for-IP leads to higher expertise if the expert equilibrium prevails under IP-for-IP. Hence, restricting trade to reciprocal exchange results in firms focusing their R&D on the market with higher commercialization ability, as the other market becomes less attractive. The result resembles the development of "spheres of influence" in the two-market context of Bernheim and Whinston (1990): The simultaneous competition of firms on multiple markets enables the firms to use strategies which reduce a firm's competitive behavior on the competitor's market. Whereas in Bernheim and Whinston (1990) the enhancement of the strategy space is via punishments in a repeated setting, it is via trading restrictions in our model.

3.2 Choosing the Terms of Trade

Assessing the optimality of free trade versus IP-for-IP involves comparing the costs and benefits of each scenario. We first consider the case of the cost structure as specified in C1 and C2. In the subsequent sections we use a specific functional form in order to derive further results.

The preceding results suggest that the allocation of investments has higher expertise under IP-for-IP than under free trade. However, it is not clear whether this yields costs or benefits. The following result shows that unless shifts in investments induced by IP-for-IP are beneficial for firm profits, free trade will always be the optimal trading scenario.

Lemma 2
For $\delta < 1$, choosing IP-for-IP forgoes gains from trade unless IP-for-IP yields $s_{ij} = 0$ for $i \neq j$.

Proof: Inspection of the payoffs in table 1 shows that post-trade payoffs under IP-for-IP are lower than under free trade for the pre-trade patent allocations $(2, \emptyset)$, $(\emptyset, 1)$, $(1, 1)$ and $(2, 2)$. ■

As IP-for-IP is potentially costly, benefits from investment decisions are required for IP-for-IP to be profitable. These benefits can arise, for example, if there are scale effects of R&D investments at the project level. In that case, focusing investments on few projects instead of lower investments in many different projects raises firm profits and makes IP-for-IP interesting for firms. Apart from the allocation across projects (captured by the definition of expertise), benefits from IP-for-IP may arise if a change in the total level of investments yields higher profits. The functional example in the following analysis captures benefits from IP-for-IP due to its effect on both, level and allocation of investments.

4 A Specific Example

For the remainder of the paper, we use the following functional form for firms' costs

$$c_i(s_i) = -\ln(1 - s_{ii}) - \ln(1 - s_{ij}) \; . \tag{C3}$$

This cost function provides a basis to derive further results on the optimality of choosing the IP-for-IP trade restriction.[9] C3 is a special case of C1 and C2 with no cost (dis-)advantages across firms. Lastly, we assume $V \geq 16$, which eases the analysis of equilibria with interior solutions.

We can now consider the costs and benefits of an IP-for-IP strategy in more detail. For benchmark purposes we first derive the optimal cooperative solution regarding the R&D investments. Joint profits are

$$E[\pi_i + \pi_j] \;\; = \;\; \sum_{k=1,2} [V(s_{ik} + s_{jk} - s_{ik}s_{jk}) + \ln(1 - s_{ik}) + \ln(1 - s_{jk})]. \tag{2}$$

[9] Technically, the cost function is undefined for $s_{ij} = 1$ $(i, j \in \{1, 2\})$. We therefore assume $\lim_{s_{ij} \to 1} c_i(s_i) = \infty$. Moreover, choice of success probability s at costs $-\ln(1 - s)$ is equivalent to the choice of R&D expenditures x and modeling the success probability as $(1 - e^{-x})$, see e.g. Kultti, Takalo, and Toikka (2007).

This is maximized if

$$(1 - s_{ik})(1 - s_{jk}) = \frac{1}{V} \tag{3}$$

with the (cooperative) investment levels

$$s_{ii}^{Coop} = \frac{V-1}{V} \quad \text{and} \quad s_{ji}^{Coop} = 0 \ \ , \ i \neq j \ . \tag{4}$$

as a specific solution to the joint optimization problem.[10] We now turn to firms' individual, non-cooperative, R&D investment decisions.

Lemma 3

1. *Under free trade, the equilibrium regarding firms' R&D investments is unique and characterized by overinvestment compared to the cooperative solution. The degree of overinvestment is increasing in δ.*

2. *Under IP-for-IP, (i) there exists an R&D equilibrium that is characterized by overinvestment in comparison to the cooperative solution for all $\delta \in [0, 1]$; (ii) for all $\delta \in [0, \hat{\delta}]$ with $\hat{\delta} \equiv \frac{2}{V+1}$, there exists an additional equilibrium with $s_{ii} = \frac{V-1}{V}$ and $s_{ij} = 0$ for $i \neq j$. The latter equilibrium thus coincides with the cooperative solution.*

Proof: See A.3

The first part of Lemma 3 establishes, for the free trade case, the standard result of R&D overinvestment in the patent race literature. Here, the patent race is asymmetric as firms have different commercialization abilities across the two projects.

Part 2 of the lemma shows that the strategic interrelation between both projects under IP-for-IP leads to multiple equilibria. One equilibrium (the "high investment equilibrium") exists over the full range of δ and results in overinvestment similar to the free trade equilibrium. For $\delta = 1$, this equilibrium coincides with the free trade equilibrium. The second equilibrium ("cooperative equilibrium") only exists if $\delta \leq \hat{\delta}$. Within this parameter range, it constitutes the expert equilibrium as it implies maximum expertise for the two firms.

[10] The optimality condition (3) implies that the allocation of investments across firms does not matter. However, if a firm incurs some (arbitrarily small) fixed cost whenever it decides to invest in a project, it is optimal that only one firm is active in each project. In this case, $s_{ik}^{Coop} = \frac{V-1}{V}$ and $s_{jk}^{Coop} = 0$ is jointly optimal.

Proposition 2
For $\delta \in [0, \hat{\delta}]$, *choice of IP-for-IP,* $s_{ii} = \frac{V-1}{V}$ *and* $s_{ij} = 0$ *for* $i \neq j$ *is a subgame perfect equilibrium.*

Proof: As this strategy combination yields the jointly optimal solution as an equilibrium, no firm has incentives to deviate. ■

The combination of Lemmas 2 and 3 implies that for $\delta \leq \hat{\delta}$, R&D competition under IP-for-IP yields profit levels as in the cooperative solution. By selecting the expert equilibrium under IP-for-IP, the firms in this example realize both the efficient level and allocation of R&D investments. The firms thus gain from committing to what appear to be ex post inefficient terms of trade.

By numerical analysis of the model, we are able to further characterize firms' optimal choice of trading scenarios: The high investment equilibrium under IP-for-IP also yields higher expertise and lower levels of overinvestment than the free trade equilibrium. However, the costs of foregone trading opportunities outweigh these benefits at the investment level. As a consequence, the choice of IP-for-IP and the high investment equilibrium levels does not constitute a subgame perfect equilibrium, as it is dominated by the (unique) free trade equilibrium. The choice of IP-for-IP by any firm in t=0 therefore also acts as a signal which coordinates the two firms to play the low investment equilibrium in the ensuing R&D game (see e.g. van Damme, 1989).

5 Cross-licensing: Feature Complementarity

The empirical motivation of the paper mainly stems from the literature on cross-licensing deals. However, in our base model, transactions take the form of outright sale of IP from one firm to another. In this section, we consider joint usage of a patent by both firms such that "trade" of IP now implies (cross-)licensing instead of a transfer of IP. This not only captures an important aspects of the market for technology but also shows that IP-for-IP is preferable to even more pronounced trade restrictions. We thus illustrate the optimality of intermediate levels of trade restrictions such as IP-for-IP.

5.1 Model Extension

To capture (cross-)licensing, that is the use of a patent by the inventing firm and at least one other firm, we assume that patent 2 contains a feature that complements patent 1, and vice versa. By using both patents, a firm may thus capture an enhanced maximum value of γV, where $\gamma \geq 1$, from each patent. The payoffs from using a single patent, however, remain the same. This is illustrated in table 2 which shows the post-trade payoffs under free trade, IP-for-IP and no trade for this (and the subsequent) extension. Payoffs only differ from the base model in case both patents exist.[11] Under free trade, firms now realize the full value of a patent plus the complementary value $(\gamma - 1)V$ in the two markets. Under IP-for-IP and asymmetric pre-trade patent allocation, the firm owning the patents realizes the fully enhanced value only in one market and the reduced value of $\delta\gamma V$ in the other market.

[Insert Table 2 about here]

Since restricting trade to reciprocal exchange can be profitable for firms, should firms also consider restricting trade in technology even further? To answer this question, we also consider the most extreme restriction, that is the commitment by firms not to trade at all. Relative to the IP-for-IP case, this commitment alters firm payoffs if each firm obtains one patent: Rather than trading the patents in order to realize gains from barter or patent complementarities, the firms commit to use only the single patent they obtained themselves. For all other allocations, the payoffs under no trade remain as in the IP-for-IP case (see table 1).[12] Lastly, let costs be as specified in C3.

5.2 Equilibrium Analysis

In a first step, we consider the equilibrium R&D investments under the no trade scenario, absent any patent complementarities, i.e. let $\gamma = 1$. We then get the

[11]Where payoffs differ from the base model, table cells are highlighted by shading.

[12]While it may seem that the no trade commitment yields no benefits, it can be shown that absent patent complementarities (i.e. for $\gamma = 1$), an expert equilibrium under no trade always exists given assumptions C1 and C2. Moreover, this expert equilibrium has higher expertise than the expert equilibrium under IP-for-IP. Details of the proof are available from the corresponding author.

following result:

Lemma 4

In case of no trade in IP and $\gamma = 1$, the no trade equilibrium is unique with investment levels continuous in δ. For $\delta \in [0, \hat{\delta}]$, the equilibrium yields the cooperative solution; for $\delta > \hat{\delta}$, the equilibrium exhibits overinvestment.

Proof: See A.4

This result illustrates that the no trade restriction also allows the firms to achieve the cooperative solution by focusing each firm's investments on its area of expertise. Hence, absent patent complementarities, both IP-for-IP and no trade yield the same equilibrium in R&D for $\delta \leq \hat{\delta}$ and, because there is no value in cross-licensing, the same payoffs.[13] We now consider how these complementarities (i.e. $\gamma > 1$) affect the trade-off between trading scenarios.

The key effect of feature complementarity is to increase the value of both patents existing. This raises R&D incentives for the firms in both R&D projects. Consequently, it is also harder for a firm to keep its competitor out of a project. The strength of this effect is now different under IP-for-IP and no trade. As will be shown, this implies that the critical value of δ where firms focus only on one market in equilibrium under IP-for-IP (now labeled $\hat{\delta}^{IP}$) and no trade ($\hat{\delta}^{NT}$) diverge. Finally, in case of free trade and IP-for-IP, the success of the R&D process has a potential positive externality for the other firm, as it raises the other patent's value if cross-licensing is agreed upon. This implies that the jointly optimal (cooperative) investment levels will differ from the equilibrium levels when only one firm is active in a project.

Proposition 3

For $\delta \in [0, \hat{\delta}^{\Theta}]$ with $\Theta \in \{IP, NT\}$, the expert equilibrium under trade restriction Θ is characterized by investment levels $s_{ii}^{*,\Theta} > 0$ and $s_{ij}^{*,\Theta} = 0$, where $i \neq j$. Evaluated at $\gamma = 1$, a marginal increase in γ has the following effects:

1. *The critical level of δ where a firm invests only in one project in equilibrium under IP-for-IP or no trade decreases. The decrease is higher under no trade than under IP-for-IP, $0 > \frac{d\hat{\delta}^{IP}}{d\gamma} > \frac{d\hat{\delta}^{NT}}{d\gamma}$.*

[13] It can be shown that absent complementarities, there exist values of $\delta > \hat{\delta}$ such that no trade yields higher payoffs than IP-for-IP. However, as the subsequent analysis shows, this does not hold under patent complementarities anymore. We thus do not pursue the no trade analysis any further.

2. *The jointly optimal investment level increases more than the IP-for-IP expert equilibrium investment level,* $\frac{ds_{ii}^{Coop}}{d\gamma} > \frac{ds_{ii}^{*,IP}}{d\gamma}$.

3. *The IP-for-IP expert equilibrium investment level increases whereas the no trade expert equilibrium level remains unaffected,* $\frac{ds_{ii}^{*,IP}}{d\gamma} > \frac{ds_{ii}^{*,NT}}{d\gamma} = 0$.

Proof: See A.5

The first result in Proposition 3 implies that it is easier to drive a competitor out of a market under IP-for-IP than under no trade. Under no trade, the only possibility to realize patent complementarities is to be successful in both projects, whereas under IP-for-IP, patent complementarities can be realized via cross-licensing. Additionally, parts 2 and 3 of the proposition imply that patent complementarities lead to an underinvestment problem under IP-for-IP and no trade. As the underinvestment is more severe under no trade, expected profits are higher under IP-for-IP than under no trade. Lastly, for γ close to one, IP-for-IP yields profits close to the jointly optimal level. As a consequence, patent complementarities and cross-licensing under IP-for-IP enable firms to realize higher profits more often than in case of no trade or free trade.

Further numerical analyses illustrate the case for IP-for-IP relative to the other trading scenarios. Table 3 provides some results of these computations. The table shows the (joint) probability of obtaining a patent in a market and the expected profits for a single firm for the three trading scenarios as well as for the case of joint decision-making. The results are presented at the two critical values $\hat{\delta}^{IP}$ and $\hat{\delta}^{NT}$ where one firm exits the other firm's market under IP-for-IP and no trade, respectively. For $\gamma = 1$, these critical values coincide and the results of the base model are replicated: both IP-for-IP and no trade yield the cooperative outcome whereas the free trade equilibrium exhibits overinvestment and lower profits.

[Insert Table 3 about here]

The numerical example illustrates how an increase in the complementary value of a patent affects equilibrium patent probabilities. With the exception of investments under no trade at (and below) $\hat{\delta}^{NT}$, all probabilities increase. However, IP-for-IP equilibrium investments now result in underinvestment relative to the cooperative solution. Nevertheless, for $\gamma > 1$, IP-for-IP now yields the highest expected profits. While no trade is still preferable to free trade for low complementarity values, it yields lowest profits for higher values of γ. The strictly higher profits under IP-for-IP thus show that there is a strong case for choosing IP-for-IP as an intermediate trade restriction under cross-licensing based on patent complementarities.

6 Asymmetric Firms

So far, the model has assumed that both firms are symmetric in all respects. Given one of our motivations in the introduction – Intel's IP-for-IP strategy – we are now interested in an asymmetric setting where one of the two firms enjoys an exogenous competitive advantage over the other firm. An important difference between large and small is the availability of specialized complementary assets (Teece, 1986). Larger firms have more assets in place and are thus able to profitably exploit a wider range of innovations that smaller firms. We capture this idea in our model by driving a wedge between both firms' commercialization abilities (δ). More precisely, we now assume that $\delta_1 = \delta \geq 0 = \delta_2$. That is, firm 2 is unable to commercialize patent 1 whereas firm 1 may still obtain a positive value from patent 2. Given this modification, firm 2's motives to invest in project 1 are reduced to obtaining patent 1 as a trading good (either in exchange for cash or IP). Under an IP-for-IP strategy, if firm 1 does not hold patent 2 then the value of patent 1 is zero for firm 2 as the latter is unable to commercialize patent 1 and trade is ruled out.[14] In contrast, firm 1 still obtains a positive value from patent 2 when trade is not possible.[15] The asymmetry introduced implies that asymmetric equilibria have to be taken into account. As the general analysis easily becomes intractable, we use numerical analyses to derive the following results (with costs as specified in C3).

Firm 1's higher commercialization ability gives it an advantage over firm 2 in both trading scenarios. Consequently, firm 1 invests more in market 2 than firm 2 invests in market 1. Under IP-for-IP, firm 1 is now able to drive its competitor out of market 1 while it remains active itself in market 2. It can be shown that

[14]As before, in this part of the analysis we assume that an IP-for-IP strategy rules out any cash payments.

[15]See table 2 for the full payoff structure.

such an equilibrium exists for $\delta \leq \hat{\delta}^{asym}$ with $\hat{\delta}^{asym} > \hat{\delta}$. As in the base model, firm 1 also also exits market 2 in the IP-for-IP expert equilibrium if $\delta \leq \hat{\delta}$. Hence, the IP-for-IP expert equilibrium is symmetric for $\delta \in [0, \hat{\delta}]$. For all other cases, equilibria are asymmetric.

While the structure of equilibria is fairly intuitive, the optimal choice of trading restrictions is more complex in case of asymmetric firms. Table 4 illustrates this for two specific numerical examples evaluated at the two critical values of δ. The results show that for a lower market value of patents ($V = 20$), firm 2 prefers IP-for-IP over free trade for a larger parameter range of δ than firm 1. It even prefers IP-for-IP for values strictly above $\hat{\delta}$: as equilibrium investments and profits are continuous in δ, the difference in firm 2 profits between IP-for-IP and free trade only becomes negative at a value of δ strictly between $\hat{\delta}$ and $\hat{\delta}^{asym}$. Firm 1 on the other hand strictly prefers free trade over IP-for-IP at $\delta = \hat{\delta}$. However, for higher market value of patents ($V = 100$), firm 1 prefers IP-for-IP for all $\delta \in [0, \hat{\delta}^{asym}]$.

[Insert Table 4 about here]

Although our numerical results show that firms' preferred trading scenario changes with the market value of patents, they also suggest that asymmetries lead to a more frequent choice of IP-for-IP: As the trading restriction can be enforced unilaterally, it suffices that one firm prefers IP-for-IP over free trade. Irrespective of the numerical parameters, this is always true for parameters of firm 1's commercialization ability in a range strictly larger than the range in the base model, $[0, \hat{\delta}]$.

7 Concluding Remarks

This paper argues that the type of currency used in technology transactions may have an impact on R&D competition among firms. In the simplest set-up, the model has two firms allocate their research budget over two R&D projects. Firms' R&D technologies are homogeneous across both projects. However, firms have heterogeneous commercialization abilities regarding the output of the two projects which enables them to realize potential gains from trade upon the completion of R&D activity. We analyze the effects that arise from a trade restricting strategy which restrains firms from using cash when trading technology. The model shows that the introduction of such an IP-for-IP strategy causes a trade-off. On the one hand, firms forego potential gains from trade as in some cases desirable trade does not take place because it would require cash transactions. On the other hand, these trade restrictions drive a wedge between the two projects and thus soften R&D competition. That is, under an IP-for-IP strategy, both firms concentrate their R&D effort on the project where they have a higher commercialization ability. The model suggests that IP-for-IP can be a profitable strategy as long as the difference between firms' commercialization abilities as well as patent complementarities are sufficiently high. In sum, we show that the way IP is traded has an impact on the creation of technology. The paper thus gives an ex-ante orientated explanation why cash might be a different currency than IP in the market for technology.

By focusing our analysis on the investment stage of the R&D process, we willingly ignored several important aspects. Probably most important is the issue of welfare implications. Our model only encompasses firms' surplus, thus disregarding consumer welfare or the social value of patents. Hence, the reduction in excessive R&D investments under IP-for-IP might be less desirable from a welfare point of view. Furthermore, more specific modeling of the post-patent competition stage can be informative for issues of competition policy. Lastly, patent infringements and litigation affect the post-R&D allocation of patents and thus affect the trading outcomes. This in turn might affect the optimal choice of trade restrictions. All the above-mentioned aspects lend themselves to future analysis.

A Appendix

A.1 Proof of Lemma 1

Part 1.: Inspection of the payoffs in table 1 shows that for $\delta = 1$, the two scenarios yield identical payoffs for each pre-trade allocation.

Part 2.: The proof proceeds as follows: We first redefine strategies such that the game can be shown to be a symmetric supermodular game. This proofs existence of symmetric extremal equilibria, e.g. see Vives (1999), Chapter 2, Theorem 2.3 and Remark 15, or Vives (2005), Section 4, Results 1 and 2. Second, we show that for any equilibrium $\tilde{s}_{ii}, \tilde{s}_{ij}$ with $\tilde{s}_{ii} < \tilde{s}_{ij}$, there exists another equilibrium with $s_{ii} > s_{ij}$. Hence, the maximum equilibrium is an expert equilibrium as defined in section 2.

Let firm i's strategy in market $j \neq i$ be $f_{ij} = 1 - s_{ij}$. Then the game starting in t=1 is supermodular in either trading scenario:

- The strategy spaces of the two firms, $[0,1]^2$, is compact.
- Firm i's profit is supermodular in its own strategies:

$$\frac{\partial^2 \pi_i^{FT}}{\partial s_{ii} \partial f_{ij}} = \frac{\partial^2 c_i}{\partial s_{ii} \partial s_{ij}} \geq 0 \tag{5}$$

  and

$$\frac{\partial^2 \pi_i^{IP}}{\partial s_{ii} \partial f_{ij}} = \frac{V}{4}(1-\delta)(1-f_{ji})(2-s_{jj}) + \frac{\partial^2 c_i}{\partial s_{ii} \partial s_{ij}} \geq 0 \tag{6}$$

- Firm i's profit is characterized by increasing differences in its competitor's strategies: for $j \neq i$,

$$\frac{\partial^2 \pi_i^{FT}}{\partial s_{ii} \partial s_{jj}} = 0 \tag{7}$$

$$\frac{\partial^2 \pi_i^{FT}}{\partial s_{ii} \partial f_{ji}} = \frac{V}{4}(3-\delta) \geq 0 \tag{8}$$

$$\frac{\partial^2 \pi_i^{FT}}{\partial f_{ij} \partial s_{jj}} = \frac{V}{4}(1+\delta) \geq 0 \tag{9}$$

$$\frac{\partial^2 \pi_i^{FT}}{\partial f_{ij} \partial f_{ji}} = 0 \tag{10}$$

and

$$\frac{\partial^2 \pi_i^{IP}}{\partial s_{ii} \partial s_{jj}} = \frac{V}{4}(1-\delta)(1-f_{ij})(1-f_{ji}) \geq 0 \tag{11}$$

$$\frac{\partial^2 \pi_i^{IP}}{\partial s_{ii} \partial f_{ji}} = \frac{V}{4}(2+(1-\delta)(1-f_{ij})(2-s_{jj})) \geq 0 \tag{12}$$

$$\frac{\partial^2 \pi_i^{IP}}{\partial f_{ij} \partial s_{jj}} = \frac{V}{4}(2\delta+(1-\delta)(2-s_{ii})(1-f_{ji})) \geq 0 \tag{13}$$

$$\frac{\partial^2 \pi_i^{IP}}{\partial f_{ij} \partial f_{ji}} = \frac{V}{4}(1-\delta)(2-s_{ii})(2-s_{jj}) \geq 0 \tag{14}$$

Extremal equilibria exist and are symmetric in a symmetric supermodular game. Hence, there exists a maximum equilibrium in either trading scenario, i.e. an equilibrium $(s_{ii}^*, f_{ij}^* = 1 - s_{ij}^*)$ with

$$s_{ii}^* \geq s_{ii}' \text{ and } f_{ij}^* \geq f_{ij}' \Leftrightarrow s_{ij}^* \leq s_{ij}' \tag{15}$$

for any other equilibrium $(s_{ii}', f_{ij}' = 1 - s_{ij}')$ where $i \neq j$.

Next, assume there exists an equilibrium with $s_{ij} > s_{ii}$ in trading scenario $\Theta \in \{FT, IP\}$. Then, the (symmetric) minimum equilibrium $(\tilde{s_{ii}}, \tilde{f_{ij}} = 1 - \tilde{s_{ij}})$ in this scenarion also has $\tilde{s_{ii}} < \tilde{s_{ij}}$ and has to satisfy

$$\left.\frac{\partial \pi_i^{\Theta}}{\partial s_{ii}}\right|_{s_{ii}=\tilde{s_{ii}}, f_{ij}=\tilde{f_{ij}}} \leq 0 \qquad \text{and} \tag{16}$$

$$\left.\frac{\partial \pi_i^{\Theta}}{\partial f_{ij}}\right|_{s_{ii}=\tilde{s_{ii}}, f_{ij}=\tilde{f_{ij}}} \leq 0 \tag{17}$$

We will now show that these conditions imply that there exists a symmetric equilibrium $(\hat{s_{ii}}, \hat{f_{ij}} = 1 - \hat{s_{ij}})$ with $\hat{s_{ii}} \geq 1 - \tilde{f_{ij}}$, $\hat{f_{ij}} \geq 1 - \tilde{s_{ii}}$, and hence $\hat{s_{ii}} > \hat{s_{ij}}$. For this equilibrium to exist, it suffices to show that

$$\left.\frac{\partial \pi_i^{\Theta}}{\partial s_{ii}}\right|_{s_{ii}=1-\tilde{f_{ij}}, f_{ij}=1-\tilde{s_{ii}}} \geq 0 \qquad \text{and} \tag{18}$$

$$\left.\frac{\partial \pi_i^{\Theta}}{\partial f_{ij}}\right|_{s_{ii}=1-\tilde{f_{ij}}, f_{ij}=1-\tilde{s_{ii}}} \geq 0 \tag{19}$$

If these two conditions are satisfied, the best response function $BR(s_{ii}, f_{ij})$ has $BR(s_{ii} = 1 - \tilde{f_{ij}}, f_{ij} = 1 - \tilde{s_{ii}}) \geq (1 - \tilde{f_{ij}}, 1 - \tilde{s_{ii}})$. As supermodularity implies increasing best response functions and there always exists a symmetric maximum equilibrium, there has to be an equilibrium at $(\hat{s_{ii}}, \hat{f_{ij}} = 1 - \hat{s_{ij}})$ as defined above.

- For free trade, (16) and (17) imply, respecively,

$$\left.\frac{\partial c_i}{\partial s_{ii}}\right|_{s_{ii}=\tilde{s_{ii}},f_{ij}=\tilde{f_{ij}}} \geq \frac{V}{4}(4-(3-\delta)(1-\tilde{f_{ij}})) \tag{20}$$

and

$$\left.\frac{\partial c_i}{\partial s_{ij}}\right|_{s_{ii}=\tilde{s_{ii}},f_{ij}=\tilde{f_{ij}}} \leq \frac{V}{4}(1+\delta)(2-\tilde{s_{ii}}) \tag{21}$$

Using these in the evaluation of (18) and (19) yields, combined with assumption C2,

$$\left.\frac{\partial \pi_i^{FT}}{\partial s_{ii}}\right|_{s_{ii}=1-\tilde{f_{ij}},f_{ij}=1-\tilde{s_{ii}}} \geq \frac{V}{2}(1-\delta)(1-\tilde{s_{ii}}) \geq 0 \tag{22}$$

and

$$\left.\frac{\partial \pi_i^{FT}}{\partial f_{ij}}\right|_{s_{ii}=1-\tilde{f_{ij}},f_{ij}=1-\tilde{s_{ii}}} \geq \frac{V}{2}(1-\delta)\tilde{f_{ij}} \geq 0 \tag{23}$$

which confirms existence of an equilibrium $(\hat{s_{ii}}, \hat{f_{ij}} = 1-\hat{s_{ij}})$ under free trade.

- For IP-for-IP, (16) and (17) imply, respecively,

$$\left.\frac{\partial c_i}{\partial s_{ii}}\right|_{s_{ii}=\tilde{s_{ii}},f_{ij}=\tilde{f_{ij}}} \geq \frac{V}{4}(4-(1-\tilde{f_{ij}})(2+(1-\delta)(1-\tilde{f_{ij}})(2-\tilde{s_{ii}}))) \tag{24}$$

and

$$\left.\frac{\partial c_i}{\partial s_{ij}}\right|_{s_{ii}=\tilde{s_{ii}},f_{ij}=\tilde{f_{ij}}} \leq \frac{V}{4}(2-\tilde{s_{ii}})(2\delta+(1-\delta)(2-\tilde{s_{ii}})(1-\tilde{f_{ij}})) \tag{25}$$

Using these in the evaluation of (18) and (19) yields, combined with assumption C2,

$$\left.\frac{\partial \pi_i^{IP}}{\partial s_{ii}}\right|_{s_{ii}=1-\tilde{f_{ij}},f_{ij}=1-\tilde{s_{ii}}} \geq \frac{V}{4}(1-\delta)(\tilde{f_{ij}}(4-2\tilde{s_{ii}})+2\tilde{s_{ii}}(1-\tilde{f_{ij}}-\tilde{s_{ii}})) \geq 0 \tag{26}$$

(because $\tilde{s_{ij}} - \tilde{s_{ii}} > 0$ implies $1-\tilde{f_{ij}}-\tilde{s_{ii}} > 0$) and

$$\left.\frac{\partial \pi_i^{IP}}{\partial f_{ij}}\right|_{s_{ii}=1-\tilde{f_{ij}},f_{ij}=1-\tilde{s_{ii}}} \geq \frac{V}{2}(1-\delta)\tilde{f_{ij}}(2(1-\tilde{s_{ii}})+(1-\tilde{f_{ij}})) \geq 0 \tag{27}$$

This confirms existence of an equilibrium $(\hat{s_{ii}}, \hat{f_{ij}} = 1-\hat{s_{ij}})$ under IP-for-IP.

These arguments show that the maximum equilibrium always has $s_{ii} \geq s_{ij}$ and is therefore always an expert equilibrium.

Part 3.: Any symmetric equilibrium $(\tilde{s_{ii}}, \tilde{s_{ij}})$ with $\tilde{s_{ii}} < \tilde{s_{ij}}$ yields a lower expected profit than a symmetric investment allocation $(s'_{ii} = \tilde{s_{ij}}, s'_{ij} = \tilde{s_{ii}})$: under free trade and IP-for-IP, the difference in profits is

$$\pi_i^{FT}(s'_{ii}, s'_{ij}) - \pi_i^{FT}(\tilde{s_{ii}}, \tilde{s_{ij}}) = c(\tilde{s_{ij}}, \tilde{s_{ii}}) - c(\tilde{s_{ii}}, \tilde{s_{ij}}) > 0 \tag{28}$$

and

$$\begin{aligned}\pi_i^{IP}(s'_{ii}, s'_{ij}) - \pi_i^{IP}(\tilde{s_{ii}}, \tilde{s_{ij}}) = {} & V(1-\delta)(1-\tilde{s_{ij}})(1-\tilde{s_{ii}})(\tilde{s_{ij}} - \tilde{s_{ii}}) \\ & + c(\tilde{s_{ij}}, \tilde{s_{ii}}) - c(\tilde{s_{ii}}, \tilde{s_{ij}}) \qquad > 0\end{aligned} \tag{29}$$

respectively, with $c(\tilde{s_{ij}}, \tilde{s_{ii}}) - c(\tilde{s_{ii}}, \tilde{s_{ij}}) > 0$ by assumption C2. Pareto-dominance follows from continuous first order conditions which are increasing in expertise when evaluated at (s'_{ii}, s'_{ij}). The latter follows directly for the minimum equilibrium from the proof of part 2.; for any other equilibrium with $\tilde{s_{ii}} < \tilde{s_{ij}}$, conditions (16) and (17) hold with equality. Consequently, (18) and (19) hold for all equilibria with $\tilde{s_{ii}} < \tilde{s_{ij}}$.

A.2 Proof of Proposition 1

First, redefine profits such that parameter $\theta \in \{1, 2\}$ specifies the trading scenario:

$$\pi_i(s_{ii}, f_{ij}, \theta) = \mathbf{1}_{\{1\}}(\theta)\pi_i^{FT} + \mathbf{1}_{\{2\}}(\theta)\pi_i^{IP} \tag{30}$$

where $\mathbf{1}_A(x)$ is an indicator function taking on the value 1 if $x \in A$ and 0 else. These profits can be shown to have increasing differences in θ for expert equilibrium investment levels:

$$\left.\frac{\partial \pi_i}{\partial s_{ii}}\right|_{\theta=2} - \left.\frac{\partial \pi_i}{\partial s_{ii}}\right|_{\theta=1} = \frac{V}{4}(1-\delta)s_{ji}(1 - s_{ij} - (1 - s_{jj})s_{ij}) > 0 \tag{31}$$

and

$$\left.\frac{\partial \pi_i}{\partial f_{ij}}\right|_{\theta=2} - \left.\frac{\partial \pi_i}{\partial f_{ij}}\right|_{\theta=1} = \frac{V}{4}(1-\delta)(2 - s_{jj})(1 - s_{ji} - (1 - s_{ii})s_{ji}) > 0 \tag{32}$$

where both inequalites hold if $s_{ii} = s_{jj} \geq s_{ij} = s_{ji}$ which is true for the expert equilibrium of each trading scenario. For supermodular games, increasing differences in an exogenous parameter imply that extremal equilibria increase in that parameter, see e.g. Vives (2005), Section 4, Result 5. Therefore, the expert equilibrium has expertise increasing in θ, i.e. when switching from free trade to IP-for-IP.

A.3 Proof of Lemma 3

Part 1.: First order conditions with respect to s_{ii} and s_{ij} $(i \neq j)$ are

$$\frac{\partial \pi_i^{FT}}{\partial s_{ii}} = \frac{V}{4}(1-s_{ii})(4-(3-\delta)s_{ji})-1=0 \tag{33}$$

$$\frac{\partial \pi_i^{FT}}{\partial s_{ij}} = \frac{V}{4}(1-s_{ij})(2-s_{jj})(1+\delta)-1=0 \tag{34}$$

The unique symmetric solution (on the interval $[0,1]$) is

$$s_{ii}^{FT} = 1-\frac{\sqrt{V^2(1+\delta)^4+32V(1+\delta)^2+64(1-\delta)^2}-V(1+\delta)^2-8(1-\delta)}{2V(1+\delta)^2} \tag{35}$$

and

$$s_{ij}^{FT} = 1-\frac{\sqrt{V^2(1+\delta)^4+32V(1+\delta)^2+64(1-\delta)^2}-V(1+\delta)^2+8(1-\delta)}{2V(1+\delta)(3-\delta)} \tag{36}$$

For $V \geq 3$ both solutions yield values within $[0,1]$.

Consider next the joint probability of obtaining a patent in project i, $1-(1-s_{ii}^{FT})(1-s_{ji}^{FT}) = s_{ii}^{FT}+s_{ji}^{FT}-s_{ii}^{FT}s_{ji}^{FT}$. Total differentiation yields

$$\frac{d[s_{ii}^{FT}+s_{ji}^{FT}-s_{ii}^{FT}s_{ji}^{FT}]}{d\delta} = (1-s_{ji}^{FT})\frac{ds_{ii}^{FT}}{d\delta}+(1-s_{ii}^{FT})\frac{ds_{ji}^{FT}}{d\delta} \tag{37}$$

Because

$$\frac{ds_{ii}^{FT}}{d\delta} = \frac{\delta(1-s_{ii})(1-s_{ji})(2-s_{ii})+(1+\delta)(2-s_{ii})}{(4-(3-\delta)s_{ji})(2-s_{ii})(1+\delta)+\delta(1+\delta)(1-s_{ii})(1-s_{ji})} > 0 \tag{38}$$

and

$$\frac{ds_{ji}^{FT}}{d\delta} = \frac{(1-s_{ji})(4-(3-\delta)s_{ji}+4(1-s_{ii})(1-s_{ji}))}{(4-(3-\delta)s_{ji})(2-s_{ii})(1+\delta)+\delta(1+\delta)(1-s_{ii})(1-s_{ji})} > 0 \tag{39}$$

R&D investments are increasing in δ, $\frac{d(s_{ii}^{FT}+s_{ji}^{FT}-s_{ii}^{FT}s_{ji}^{FT})}{d\delta} > 0$. Finally, compare the absolute level of the joint probability of obtaining a patent in the free trade case for $\delta = 0$ with the cooperative level: $1-(1-s_{ii}^{FT}|_{\delta=0})(1-s_{ji}^{FT}|_{\delta=0}) > 1-(1-s_{ii}^{Coop})(1-s_{ji}^{Coop})$ if

$$\frac{(\sqrt{V^2+32V+64}-V)^2-64}{12V^2} < \frac{1}{V} \tag{40}$$

which is true if $V > 3$. As this implies overinvestment at the lower boundary of the joint patent probability, there is overinvestment in the overall free trade case.

Part 2.: First order conditions for the IP-for-IP case are

$$\frac{\partial \pi_i^{IP}}{\partial s_{ii}} = \frac{V}{4}(1 - s_{ii})(4 - s_{ji}(2 + (1 - \delta)s_{ij}(2 - s_{jj}))) - 1 = 0 \tag{41}$$

$$\frac{\partial \pi_i^{IP}}{\partial s_{ij}} = \frac{V}{4}(1 - s_{ij})(2 - s_{jj})(2\delta + (1 - \delta)s_{ji}(2 - s_{ii})) - 1 = 0 \tag{42}$$

We proceed as follows: Here, we show that for $\delta \leq \hat{\delta}$, there exists an equilibrium which yields the cooperative solution. As the proof that there exists an equilibrium over the full range of δ which results in overinvestment is rather extensive, it is omitted here and made available upon request from the corresponding author.

An equilibrium with firm i active in market i only exists if

$$\left.\frac{\partial \pi_i^{IP}}{\partial s_{ii}}\right|_{s_{ij}=s_{ji}=0, s_{jj}=s_{ii}} = 0 \tag{43}$$

and

$$\left.\frac{\partial \pi_i^{IP}}{\partial s_{ij}}\right|_{s_{ij}=s_{ji}=0, s_{jj}=s_{ii}=s_{ii}^m} \leq 0 \tag{44}$$

are satisfied, where s_{ii}^m denotes the solution to (43). Using (41), (43) yields $s_{ii}^m = \frac{V-1}{V}$, and hence (44) is fullfilled if

$$\delta \leq \frac{2}{V+1} \equiv \hat{\delta} \tag{45}$$

For $\delta \in [0, \hat{\delta}]$, the cooperative solution is thus also an equilibrium.

A.4 Proof of Lemma 4

First order conditions with respect to s_{ii} and s_{ij} $(i \neq j)$ are

$$\frac{\partial \pi_i^{FT}}{\partial s_{ii}} = \frac{V}{2}(1 - s_{ii})(2 - s_{ji}) - 1 = 0 \tag{46}$$

$$\frac{\partial \pi_i^{FT}}{\partial s_{ij}} = \frac{V}{2}\delta(1 - s_{ij})(2 - s_{jj}) - 1 = 0 \tag{47}$$

The unique symmetric equilibrium (on the interval $[0, 1]$) is

$$s_{ii}^{NT} = 1 - \frac{\sqrt{16\delta + (\delta(V + 2) - 4)^2} - \delta V - 2(1 + \delta)}{2\delta V} \tag{48}$$

and

$$s_{ij}^{NT} = 1 - \frac{\sqrt{16\delta + (\delta(V+2)-4)^2} + \delta V - 2(1+\delta)}{2\delta V} \tag{49}$$

for $\delta > \hat{\delta}$. At $\delta = \hat{\delta}$, (48) and (49) yield $s_{ii}^{NT} = \frac{V-1}{V}$ and $s_{ij}^{NT} = 0$, i.e. the cooperative solution, which is also the equilibrium for $\delta < \hat{\delta}$.

Finally, for $\delta \geq \hat{\delta}$,

$$\frac{d(s_{ii}^{NT} + s_{ji}^{NT} - s_{ii}^{NT} s_{ji}^{NT})}{d\delta} = \frac{(1-s_{ii}^{NT})(2-s_{ii}^{NT})(1-s_{ji}^{NT})}{\delta(3-s_{ii}^{NT}-s_{ji}^{NT})} > 0 \tag{50}$$

which implies overinvestment inequilibrium if $\delta > \hat{\delta}$.

A.5 Proof of Proposition 3

We first derive the "monopoly" investment levels $s_{ii}^{*,\Theta}$ and critical values $\hat{\delta}^{\Theta}$ where firm i exits market $j \neq i$: Solving

$$\left.\frac{\partial \pi_i^{\Theta}}{\partial s_{ii}}\right|_{s_{ij}=s_{ji}=0, s_{jj}=s_{ii}} = 0 \tag{51}$$

for s_{ii} yields $s_{ii}^{*,\Theta}$. This can only be an equilibrium if

$$\left.\frac{\partial \pi_i^{\Theta}}{\partial s_{ij}}\right|_{s_{ii}=s_{jj}=s_{ii}^{*,\Theta}, s_{ij}=s_{ji}=0} \leq 0 \tag{52}$$

which yields the condition $\delta \leq \hat{\delta}^{\Theta}$. For $\Theta \in \{IP, NT\}$, these steps result in

$$s_{ii}^{*,IP} = \frac{V\gamma + \sqrt{V}\sqrt{4-4\gamma+V\gamma^2} - 2V}{2(V\gamma - V)} \tag{53}$$

$$\hat{\delta}^{IP} = \frac{2(V\gamma - \sqrt{V}\sqrt{4-4\gamma+V\gamma^2})}{(\gamma-1)(2+V\gamma+\sqrt{V}\sqrt{4-4\gamma+V\gamma^2})} \tag{54}$$

and

$$s_{ii}^{*,NT} = \frac{V-1}{V} \tag{55}$$

$$\hat{\delta}^{NT} = \frac{\gamma - 1 + 2V - V^2(\gamma-1)}{1-\gamma+V+V^2\gamma} \tag{56}$$

Similarly, the jointly optimal investment level, with $s_{ij}^{Coop} = s_{ji}^{Coop} = 0$, can be derived by solving

$$\left.\frac{\partial(\pi_i + \pi_j)}{\partial s_{ii}}\right|_{s_{ij}=s_{ji}=0, s_{jj}=s_{ii}} = 0 \tag{57}$$

for s_{ii}. This yields

$$s_{ii}^{Coop} = \frac{3V - 2V\gamma - \sqrt{V}\sqrt{8 + V - 8\gamma - 4V\gamma + 4V\gamma^2}}{2(2V\gamma - 2V)} \tag{58}$$

By L'Hôpital's rule, one can show that for $\gamma = 1$, $s_{ii}^{Coop} = s_{ii}^{*,IP} = s_{ii}^{*,NT} = \frac{V-1}{V}$ and $\hat{\delta}^{IP} = \hat{\delta}^{NT} = \hat{\delta}$.

Part 1.: Differentiating $\hat{\delta}^{IP}$ and $\hat{\delta}^{NT}$ with respect to γ at $\gamma = 1$ yields

$$\left.\frac{d\hat{\delta}^{IP}}{d\gamma}\right|_{\gamma=1} = -2\frac{2V^2 - 1 - V}{V(V+1)^2} < 0 \tag{59}$$

and

$$\left.\frac{d\hat{\delta}^{NT}}{d\gamma}\right|_{\gamma=1} = -\frac{V^2 + 2V - 3}{V + V^2} < 0 \tag{60}$$

Similarly,

$$\left.\frac{d(\hat{\delta}^{IP} - \hat{\delta}^{NT})}{d\gamma}\right|_{\gamma=1} = \frac{V^3 - V^2 + V - 1}{V(V+1)^2} > 0 \tag{61}$$

Parts 2. and 3.: Differentiating s_{ii}^{Coop}, $s_{ii}^{*,IP}$ and $s_{ii}^{*,NT}$ with respect to γ at $\gamma = 1$ yields

$$\left.\frac{ds_{ii}^{Coop}}{d\gamma}\right|_{\gamma=1} = 2\frac{V-1}{V^2} > 0 \tag{62}$$

$$\left.\frac{ds_{ii}^{*,IP}}{d\gamma}\right|_{\gamma=1} = \frac{V-1}{V^2} > 0 \tag{63}$$

$$\left.\frac{ds_{ii}^{*,NT}}{d\gamma}\right|_{\gamma=1} = 0 \tag{64}$$

and

$$\left.\frac{d(s_{ii}^{Coop} - s_{ii}^{*,IP})}{d\gamma}\right|_{\gamma=1} = \frac{V-1}{V^2} > 0 \tag{65}$$

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(ω_1, ω_2)	$p(\omega_1, \omega_2)$	$\pi_i(\omega_1, \omega_2)$	
		Free trade	IP-for-IP
$(\emptyset, \emptyset)$	$(1 - s_{11})(1 - s_{21})(1 - s_{12})(1 - s_{22})$	$\pi_1 = 0$ $\pi_2 = 0$	$\pi_1 = 0$ $\pi_2 = 0$
$(1, \emptyset)$	$(s_{11}(1 - s_{21}) + \frac{1}{2}s_{11}s_{21})(1 - s_{12})(1 - s_{22})$	$\pi_1 = V$ $\pi_2 = 0$	$\pi_1 = V$ $\pi_2 = 0$
$(2, \emptyset)$	$(s_{21}(1 - s_{11}) + \frac{1}{2}s_{21}s_{11})(1 - s_{12})(1 - s_{22})$	$\pi_1 = \frac{1-\delta}{2}V$ $\pi_2 = \frac{1+\delta}{2}V$	$\pi_1 = 0$ $\pi_2 = \delta V$
$(\emptyset, 2)$	$(1 - s_{11})(1 - s_{21})(s_{22}(1 - s_{12}) + \frac{1}{2}s_{12}s_{22})$	$\pi_1 = 0$ $\pi_2 = V$	$\pi_1 = 0$ $\pi_2 = V$
$(\emptyset, 1)$	$(1 - s_{11})(1 - s_{21})(s_{12}(1 - s_{22}) + \frac{1}{2}s_{12}s_{22})$	$\pi_1 = \frac{1+\delta}{2}V$ $\pi_2 = \frac{1-\delta}{2}V$	$\pi_1 = \delta V$ $\pi_2 = 0$
$(1, 1)$	$(s_{11}(1 - s_{21}) + \frac{1}{2}s_{11}s_{21})(s_{12}(1 - s_{22}) + \frac{1}{2}s_{12}s_{22})$	$\pi_1 = \frac{3+\delta}{2}V$ $\pi_2 = \frac{1-\delta}{2}V$	$\pi_1 = (1+\delta)V$ $\pi_2 = 0$
$(2, 2)$	$(s_{21}(1 - s_{11}) + \frac{1}{2}s_{21}s_{11})(s_{22}(1 - s_{12}) + \frac{1}{2}s_{12}s_{22})$	$\pi_1 = \frac{1-\delta}{2}V$ $\pi_2 = \frac{3+\delta}{2}V$	$\pi_1 = 0$ $\pi_2 = (1+\delta)V$
$(2, 1)$	$(s_{12}(1 - s_{22}) + \frac{1}{2}s_{12}s_{22})(s_{21}(1 - s_{11}) + \frac{1}{2}s_{21}s_{11})$	$\pi_1 = V$ $\pi_2 = V$	$\pi_1 = V$ $\pi_2 = V$
$(1, 2)$	$(s_{11}(1 - s_{21}) + \frac{1}{2}s_{11}s_{21})(s_{22}(1 - s_{12}) + \frac{1}{2}s_{12}s_{22})$	$\pi_1 = V$ $\pi_2 = V$	$\pi_1 = V$ $\pi_2 = V$

Table 1: Patent allocations and payoffs

(ω_1, ω_2)	Feature Complementarity $\pi_i(\omega_1, \omega_2)$			Asymmetric Firms $\pi_i(\omega_1, \omega_2)$	
	Free trade	IP-for-IP	No trade	Free trade	IP-for-IP
$(\emptyset, \emptyset)$	$\pi_1 = 0$ $\pi_2 = 0$	$\pi_1 = 0$ $\pi_2 = 0$	$\pi_1 = 0$ $\pi_2 = 0$	$\pi_1 = 0$ $\pi_2 = 0$	$\pi_1 = 0$ $\pi_2 = 0$
$(1, \emptyset)$	$\pi_1 = V$ $\pi_2 = 0$	$\pi_1 = V$ $\pi_2 = 0$	$\pi_1 = V$ $\pi_2 = 0$	$\pi_1 = V$ $\pi_2 = 0$	$\pi_1 = V$ $\pi_2 = 0$
$(2, \emptyset)$	$\pi_1 = \frac{1-\delta}{2}V$ $\pi_2 = \frac{1+\delta}{2}V$	$\pi_1 = 0$ $\pi_2 = \delta V$	$\pi_1 = 0$ $\pi_2 = \delta V$	$\pi_1 = \frac{1}{2}V$ $\pi_2 = \frac{1}{2}V$	$\pi_1 = 0$ $\pi_2 = 0$
$(\emptyset, 2)$	$\pi_1 = 0$ $\pi_2 = V$	$\pi_1 = 0$ $\pi_2 = V$	$\pi_1 = 0$ $\pi_2 = V$	$\pi_1 = 0$ $\pi_2 = V$	$\pi_1 = 0$ $\pi_2 = V$
$(\emptyset, 1)$	$\pi_1 = \frac{1+\delta}{2}V$ $\pi_2 = \frac{1-\delta}{2}V$	$\pi_1 = \delta V$ $\pi_2 = 0$	$\pi_1 = \delta V$ $\pi_2 = 0$	$\pi_1 = \frac{1+\delta}{2}V$ $\pi_2 = \frac{1-\delta}{2}V$	$\pi_1 = \delta V$ $\pi_2 = 0$
$(1, 1)$	$\pi_1 = \frac{3+\delta}{2}\gamma V$ $\pi_2 = \frac{1-\delta}{2}\gamma V$	$\pi_1 = (1+\delta)\gamma V$ $\pi_2 = 0$	$\pi_1 = (1+\delta)\gamma V$ $\pi_2 = 0$	$\pi_1 = \frac{3+\delta}{2}V$ $\pi_2 = \frac{1-\delta}{2}V$	$\pi_1 = (1-\delta)V$ $\pi_2 = 0$
$(2, 2)$	$\pi_1 = \frac{1-\delta}{2}\gamma V$ $\pi_2 = \frac{3+\delta}{2}\gamma V$	$\pi_1 = 0$ $\pi_2 = (1+\delta)\gamma V$	$\pi_1 = 0$ $\pi_2 = (1+\delta)\gamma V$	$\pi_1 = \frac{1}{2}V$ $\pi_2 = \frac{3}{2}V$	$\pi_1 = 0$ $\pi_2 = V$
$(2, 1)$	$\pi_1 = \gamma V$ $\pi_2 = \gamma V$	$\pi_1 = \gamma V$ $\pi_2 = \gamma V$	$\pi_1 = \delta V$ $\pi_2 = \delta V$	$\pi_1 = (1+\frac{\delta}{2})V$ $\pi_2 = (1-\frac{\delta}{2})V$	$\pi_1 = V$ $\pi_2 = V$
$(1, 2)$	$\pi_1 = \gamma V$ $\pi_2 = \gamma V$	$\pi_1 = \gamma V$ $\pi_2 = \gamma V$	$\pi_1 = V$ $\pi_2 = V$	$\pi_1 = V$ $\pi_2 = V$	$\pi_1 = V$ $\pi_2 = V$

Table 2: Extensions: Patent allocations and payoffs (shaded cells indicate changes from the base model)

	$\gamma = 1.00$	$\gamma = 1.01$	$\gamma = 1.10$
Jointly optimal patent probability	0.938	0.939	0.947
Patent probability at $\delta = \hat{\delta}^{NT}$			
Free trade	0.971	0.971	0.973
IP-for-IP	0.938	0.938	0.943
No trade	0.938	0.938	0.938
Patent probability at $\delta = \hat{\delta}^{IP}$			
Free trade	0.971	0.971	0.975
IP-for-IP	0.938	0.938	0.943
No trade	0.938	0.940	0.952
Jointly optimal firm profits	12.227	12.368	13.649
Firm profits at $\delta = \hat{\delta}^{NT}$			
Free trade	11.995	12.142	13.469
IP-for-IP	12.227	12.368	13.646
No trade	12.227	12.227	12.227
Firm profits at $\delta = \hat{\delta}^{IP}$			
Free trade	11.995	12.137	13.426
IP-for-IP	12.227	12.368	13.646
No trade	12.227	11.740	9.655

Table 3: Feature complementarity: Numerical results for $V = 16$

	$V=20$	$V=100$
Jointly optimal firm profits	16.004	94.395
Firm 1 profits at $\delta = \hat{\hat{\delta}}$		
Free trade	16.204	93.759
IP-for-IP	16.004	94.395
Firm 1 profits at $\delta = \hat{\hat{\delta}}^{asym}$		
Free trade	16.298	93.779
IP-for-IP	16.025	94.396
Firm 2 profits at $\delta = \hat{\hat{\delta}}$		
Free trade	15.274	92.769
IP-for-IP	16.004	94.395
Firm 2 profits at $\delta = \hat{\hat{\delta}}^{asym}$		
Free trade	15.167	92.749
IP-for-IP	14.293	92.454

Table 4: Asymmetric firms: Numerical results