R&D Competition and Strategic Trade Restrictions in the Market for Technology*

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Abstract

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 – for example in cross-licensing agreements. This paper suggests that the choice of 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 and thus soften R&D competition. However, this strategy forgoes potential gains from trade when IP is distributed asymmetrically. By providing a simple model of the trade-offs involved, this paper shows that IP-for-IP is profitable in industries (1) where firms differ in their commercialization abilities; (2) where patent complementarities are less pronounced.

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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 most 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.

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 (in addition to affecting post-innovation issues such as litigation, as suggested by prior literature).

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 across these different markets. 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.

[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.

This creates a positive level-effect on R&D expenditures. Our analysis suggests that strategies of restricting trade in technologies to reciprocal exchange can be profit-enhancing. This is particularly the case in industries (1) where firms differ in their commercialization abilities; (2) where patent complementarities (that is the value added by additional patents) are less pronounced.

There is a growing body of literature that studies the impact of technology licensing and intellectual property design on market structure and welfare. Inter alia, this literature emphasizes the special role of cross-licensing agreements in promoting freedom to design and manufacture products in the presence of patent thickets and thus in enhancing efficiency in high-tech industries such as semiconductors and electronics. According to Grindley and Teece (1997, p.23), "[t]o 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 argue that IBM acquires necessary outside IP rights "primarily by trading access to its own patents, a process called 'cross-licensing'." 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] This treatment of cross-licensing agreements in the literature raises the question whether there is more to cross-licensing than the mere composition of two distinct licensing deals. Put differently, many articles in that field do not explicitly explain 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. Our model contributes to this 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

[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."

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 model, these models are not concerned with project choice in R&D. There is also a literature focusing on project choice rather than the level of investments in R&D. As Anderson and Cabral (2007) put it, "[...] from a manager's point of view, the decision is not just how much to spend on R&D but also how to spend it". This paper and others (e.g. Bhattacharya and Mookherjee, 1986; Dasgupta and Maskin, 1987; Cabral, 2003; Gerlach, Ronde, and Stahl, 2005) 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. However, the value of technology as a tradeable good depends on the terms of trade. An IP-for-IP strategy affects this value and thus 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.

This 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 and then focuses on the profitability of an IP-for-IP based strategy. Extensions to the basic model are presented in section 4. Finally, section 5 concludes.

2 Model

We consider two firms ($i = A, B$) that are potentially engaged in two research projects ($j = 1, 2$). Each project stochastically yields at most one patent which

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

covers the whole R&D output of a project.[4] This R&D process is sufficiently uncertain such that the outcome is non-contractible. Firms are homogenous with respect to their unconditional success probabilities for both projects. The maximum (market) value of either patent is symmetric and given by V. However, firms have heterogenous commercialization abilities regarding both patents. We assume that firm A (firm B) can fully exploit the value of patent 1 (2) whereas it might face a commercialization disability regarding patent 2 (1). The commercialization disability is captured in a discount factor, $\delta \in [0, 1]$.

2.1 Timing and Solution Concept

The time structure of the game is as follows:

- 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. All payoffs are realized hereafter.

We are looking at subgame perfect equilibria of the game in order to determine when trade restricting strategies (described below) 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 focus on symmetric Nash equilibria.

We assume that firms can commit themselves to the terms of trade set in t=0 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. This might be achieved by posting a reputation bond which is forfeited upon deviation from their initial choice or 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.[5]

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

[5] See e.g. the discussion in Maskin and Tirole (1999) about how renegotiation can be avoided.

We will discuss at the end of section 3 how our results may be rationalized in an infinitely repeated game framework.

2.2 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.[6] In our model, the terms of trade in technology chosen in t=0 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 trade 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 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. As this 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.

2.3 R&D Technology

Firms decide about the unconditional probability of success in each project directly which induces R&D costs. Let the unconditional success probability of firm A for project j ($j = 1, 2$) be $a_j \in [0, 1]$ with cost $c(a_j) = -\ln(1 - a_j)$. Likewise, firm B is successful on project j with probability $b_j \in [0, 1]$ at cost $c(b_j) = -\ln(1 - b_j)$. Furthermore, if both firms are successful on a certain project then each firm obtains the respective patent with probability $\frac{1}{2}$.[7] This combination of choice of success probability and specific cost function implies

[6] 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 4.

[7] This implies that, for example, the probability of firm A obtaining a patent in market 1 conditional on firm B's expenditures is $a_1(1 - \frac{1}{2}b_1)$.

that the overall (joint) success probability on a certain project does only depend on the total level of R&D investments but not on its allocation over firms.[8]

3 Analysis

In the following, we consider equilibrium R&D expenditures under the free trade (section 3.1) and the IP-for-IP (section 3.2) scenario. In section 3.3, the optimal choice of the terms of trade is characterized.

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 $\omega_j \in \Omega \equiv \{\emptyset, A, B\}$ 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 and $\pi_i(\omega_1, \omega_2)$ firm i's *post-trade* payoff from this allocation. Then firm i's expected profit in the R&D stage is

$$E[\pi_i] = \sum_{\omega_1 \in \Omega} \sum_{\omega_2 \in \Omega} p(\omega_1, \omega_2)\pi_i(\omega_1, \omega_2) \tag{1}$$

Finally, the payoffs $\pi_i(\omega_1, \omega_2)$ depend on the trade scenario and will be specified below.

3.1 Free Trade

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. Table 1 provides the probabilities and payoffs to the two firms for all possible patent allocations. Consider for example allocation $(\emptyset, A)$: in this case, firm A gains the patent for market 2 and values it at δV. As firm B's valuation is higher, they trade and split the gains, $(1 - \delta)V$, equally. Similarly, for allocation (B, B), firm B sells the patent for market 1 to firm A. And in case of allocation (B, A), the two firms exchange the patents gained in R&D, without money changing hands due to symmetric valuations.[9]

[8] Choice of success probability at these costs is equivalent to the choice of R&D expenditures x and modeling success probability as $(1 - e^{-x})$, see e.g. Kultti, Takalo, and Toikka (2007).

[9] We consider asymmetric valuations in section 4.

Cooperative solution: For benchmark purposes we first derive the optimal cooperative solution regarding the R&D investments per project. Joint profits are

$$E[\pi_A + \pi_B] \;=\; \sum_{j=1,2} [V(a_j + b_j - a_j b_j) + \ln(1 - a_j) + \ln(1 - b_j)]. \qquad (2)$$

This is maximized at

$$(1 - a_j^{Coop})(1 - b_j^{Coop}) = \frac{1}{V} \qquad (3)$$

with $V \geq 1$ to ensure non-negative investments.

Non-cooperative solution: We now turn to firms' individual, non-cooperative, R&D investment decisions in case of free trade. Individual expected profits are given in (1) and table 1. Maximization of expected profits yields the following relations[10]

$$c'(a_1) \;=\; c'(b_1) + 2\frac{(1-\delta)}{(1+\delta)} \qquad (4)$$

$$c'(b_2) \;=\; c'(a_2) + 2\frac{(1-\delta)}{(1+\delta)} \qquad (5)$$

where $\frac{(1-\delta)}{(1+\delta)} \in [0, 1]$. Given the convexity of the cost function, these relations show that a firm invests more in a project than its rival if this firm is enjoying a higher commercialization ability regarding the R&D output of the project. If $\delta = 1$ then firms invest identical amounts in either project. 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. That is, free trade leads to R&D competition over two distinct patents. Within a certain research project, one of the firms enjoys a comparative advantage over the other firm as it has a higher commercialization ability regarding the R&D output of the project. It is thus not surprising that the firm with the higher commercialization ability invests more in the respective R&D project than its competitor.

Proposition 1 *Let $V > 3$. Under free trade, the symmetric 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.*

[10]For a derivation see A.1

Proof: See A.2.

Proposition 1 restores 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.

3.2 IP-for-IP

Under IP-for-IP, gains from trade can only be realized if trade takes place on a reciprocal basis. The payoffs in this scenario differ from the free trade payoffs in some but not all states of the world as long as firms have different commercialization ability regarding the two patents (i.e. as long as $\delta < 1$). Table 1 shows the post-trade payoffs of the two firms for all possible patent allocations. Consider again the three previous examples, $(\emptyset, A)$, (B, B), and (B, A): in the first case, firm A is the owner of the only patent. Even though B would value the patent more, there is no possibility to barter, so firm A uses the patent itself at the reduced value of δV. A similar situation arises under (B, B) for firm B. As it holds both patents, there is no possibility to barter, so it keeps both patents even though patent 1 would be valued more highly at firm A. Finally, in case of (B, A), the two firms are able to reciprocally exchange their patents and realize their full value.

Firms' individual expected profits are as defined in (1), with the payoffs given in table 1. We now restrict the analysis to symmetric equilibria of R&D competition under the IP-for-IP regime, i.e. to equilibria where $a_2 = b_1$ and $b_2 = a_1$.

Lemma 1 *For $\delta = 1$, first order conditions under IP-for-IP are identical to those under free trade implying that the respective IP-for-IP equilibrium is the same as under free trade.*

Proof: See A.3

For $\delta = 1$ firms can commercialize either patent at full value. This makes trade redundant as in this case there are no gains from trade. This, in turn, implies that IP-for-IP based trade restrictions are ineffective if $\delta = 1$. However, for all $\delta < 1$, IP-for-IP changes the nature of R&D competition between firms A and B as it changes the structure of expected payoffs. 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. This lowers the expected private value of the patent that can not be fully exploited. This in turn weakens the R&D incentives regarding one of the two projects. The introduction of IP-for-IP based trade restrictions strategically interlinks both research projects since the ability to trade a certain patent depends on the distribution of patents over both projects.

Proposition 2 (i) *For all* $\delta \in [0,1]$ *there exists an R&D equilibrium that is characterized by R&D overinvestment in comparison to the cooperative solution.* (ii) *For all* $\delta \in [0, \frac{2}{V+1}]$ *there exists an additional equilibrium in firms' R&D investments. This equilibrium also leads to overinvestment as long as* $\delta < \frac{2}{V+1}$*. At* $\delta = \frac{2}{V+1}$ *it coincides with the cooperative solution.*

Proof: See A.4

According to proposition 2, for all $\delta < 1$ except $\delta = \frac{2}{V+1}$, firms overinvest in R&D compared to the cooperative solution. The strategic interrelation between both projects under IP-for-IP leads to two equilibria as long as δ is sufficiently small. One equilibrium (henceforth called "high investment equilibrium") exists over the full range of δ whereas the second equilibrium ("low investment equilibrium") does not exist if $\delta > \frac{2}{V+1}$.[11] At $\delta = \frac{2}{V+1}$ the low investment equilibrium leads to perfect coordination between the firms, i.e. both firms' equilibrium behavior coincides with the cooperative solution. That is, firm A (firm B) succeeds with probability $1 - 1/V$ (zero) in project 1 and zero ($1 - 1/V$) in project 2.

Corollary 1 *(i) Let* $\delta = 1$*. Then, a marginal reduction in* δ *lowers firms' total R&D investments in both the free trade scenario and under IP-for-IP. However, the decrease in total R&D investments is larger under IP-for-IP than under free trade. (ii) Consider the low investment IP-for-IP equilibrium at* $\delta = \frac{2}{V+1}$ *(where* $a_1 = b_2 = 1 - 1/V$ *and* $b_1 = a_2 = 0$*). Then, a marginal reduction in* δ *lowers* a_1 *and* b_2*, raises* a_2 *and* b_1*, and leads to an increase in overall R&D investments.*

[11] Note that apart from potential asymmetric equilibria, there exists also a third symmetric equilibrium where firm A (firm B) only invests in market 1 (market 2). This equilibrium reproduces the cooperative solution for all $\delta \leq \frac{2}{V+1}$. However, this equilibrium is due to the finite marginal cost at a success probability of zero. If the cost function is adjusted such that marginal cost is zero at probability zero, this third equilibrium does not exist any more, while the other two prevail. Due to tractability of the analysis, the finite marginal cost form is used in the paper nevertheless.

Proof: See A.5

Corollary 1 illustrates the structure of the IP-for-IP equilibria in relation to the equilibrium under free trade. At $\delta = 1$, a decrease in δ leads to a stronger reduction in total R&D investments under IP-for-IP than under free trade, hence the joint success probability is smaller under IP-for-IP than under free trade. At $\delta = \frac{2}{V+1}$, both IP-for-IP equilibria exist, with total R&D investments inversely related to δ in the low expenditure equilibrium. Figure 1 presents the results derived so far. It shows the joint success probability in the three (symmetric) equilibria for $V = 16$.[12] For $\delta \leq [\frac{2}{V+1} = 2/17]$ it shows both IP-for-IP equilibria (for $\delta > 2/17$, there is only the high investment equilibrium). Both are characterized by lower investments than under free trade. At $\delta = 2/17$ the low investment equilibrium coincides with the cooperative solution.

3.3 Choosing the Terms of Trade

Assessing the optimality of free trade versus IP-for-IP involves summing up the costs and benefits of each scenario. The major trade-off involved in the decision of free trade versus IP-for-IP can be described as dampened R&D competition in terms of lower investment levels versus potentially forgone gains from trade. The costs of IP-for-IP are defined by the forgone gains from trade and depend on δ in two aspects. Firstly, δ directly determines the proportion of V that a firm can commercialize if trade is desirable but not possible due to trade restrictions. Secondly, equilibrium investment levels depend on δ which alters the probability that a situation occurs where gains from trade remain unexploited.

Lemma 2 *For $\delta = 1$, the costs of IP-for-IP are zero. At $\delta = \frac{2}{V+1}$, IP-for-IP causes strictly positive costs in the high investment equilibrium and zero costs in the low investment equilibrium.*

Proof: See A.6

The combination of proposition 2 and lemma 2 implies that for $\delta = \frac{2}{V+1} > 0$, R&D competition under IP-for-IP yields the cooperative profit level for each firm. Figure 2 illustrates the expected profits under each scenario. In the high

[12] When considering joint probabilities, the probability of one firm obtaining a patent equals the joint success probability)

investment equilibrium, IP-for-IP leads to lower expected profits than under free trade as long as $\delta < 1$. For $\delta = 1$ IP-for-IP based trade restrictions are ineffective and yield the same expected profits as under free trade. In the low investment equilibrium, an IP-for-IP strategy is more profitable than free trade for $\delta = \frac{2}{V+1}$.

Proposition 3 *For $\delta = \frac{2}{V+1}$, choosing the IP-for-IP scenario and the low investment equilibrium R&D levels is a subgame perfect equilibrium.*

Proof: See A.7

This result suffices to show that firms may gain from committing to what appear to be ex post inefficient terms of trade. Given the results from our numerical analysis (as represented in figure 2), we are able to provide even further characterizations of firms' optimal choice of trading scenarios: (1) There exists a critical $\delta_0 < \frac{2}{V+1}$ such that for all $\delta \in (\delta_0, \frac{2}{V+1}]$ IP-for-IP is the most profitable strategy.[13] Hence, there is a parameter range for δ where IP-for-IP and the low investment equilibrium form a subgame perfect equilibrium. (2) As the high investment equilibrium produces lower profits than either the free trade scenario (except for $\delta = 1$) or the low investment equilibrium, we can also conclude that choosing free trade and corresponding R&D investments is a subgame perfect equilibrium for all levels of δ. (3) 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. As a consequence, the choice of IP-for-IP by any firm in t=0 of the game 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).

Lastly, the above results can be used to construct equilibria in a repeated game version of the model: Consider a repeated extensive game that starts with R&D investment decisions and where firms announce their trading intentions after patents have been allocated. For values of δ where the low investment IP-for-IP equilibrium yields higher profits than free trade, the following strategy supports restricting oneself to IP-for-IP and the corresponding low investment equilibrium R&D levels for discount factors sufficiently close to one: each player invests according to the low investment equilibrium and only suggests trade if it is reciprocal (barter). Players continue to do so in all following repetitions unless

[13] Numerical calculations show that for sufficiently high values of V, δ_0 is negative.

the competitor suggests a one-sided cash trade. Once a competitor suggested to trade for cash, each player invests according to the free trade equilibrium and always suggests to trade if gains from trade exist. This free trade equilibrium is played in all repetitions of the game thereafter. As the gains from playing IP-for-IP outweigh those from deviation (realizing gains from trade once and realizing free trade payoffs thereafter), IP-for-IP may be supported in a repeated game instead of assuming a commitment mechanism.

4 Extensions

In what follows, we consider some extensions to our model. The first two extensions incorporate two important aspects of the market for technology. First, we allow for joint usage of a patent by both firms such that "trade" of IP now implies cross-licensing instead of a tranfer of IP. Second, we introduce firm heterogeneity by allowing the two firms to differ in their commercialization abilities. Both extensions are solved numerically.

4.1 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. 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 and IP-for-IP for the base model and the extensions.[14] Payoffs only differ from the base model in case both patents exist. Under free trade, firms now realize twice the full value of a patent plus the complementary value $(1 - \gamma)V$. 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.

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

The structure of the equilibria under free trade and IP-for-IP remains as in the base model. 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. Figure 3 shows the resulting net gain for a firm from choosing IP-for-IP (and low investment equilibrium R&D levels) versus free trade. Starting from no complementary value ($\gamma = 1$, i.e. the base model), an increase in γ leads to a shift of the net payoff curve to the left. In sum, the introduction of cross-licensing via feature complementarity requires firms to differ more in terms of commercialization abilities in order for IP-for-IP to be attractive.

4.2 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 – one may wonder if firms are indeed symmetric in reality. Therefore, in this part of the analysis we are interested in an asymmetric setting where one of the two firms enjoys an exogenous competitive advantage over the other firm. As our core model focuses on the commercialization ability of both firms (δ), we drive a wedge between both firms' abilities to commercialize patents. More precisely, we now assume that $\delta_A > \delta_B = 0$. That is, firm B is unable to commercialize patent 1 whereas firm A still obtains a strictly positive value from patent 2. Given this modification, firm B'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 A does not hold patent 2 then the value of patent 1 is zero for firm B as the latter is unable to commercialize patent 1 and trade is ruled out.[15] In contrast, firm A still obtains a positive value from patent 2 when trade is not possible.[16] This type of asymmetry gives firm A an advantage over firm B under an IP-for-IP strategy. Our numerical results show that firm A has higher incentives to employ an IP-for-IP trade restriction than firm B (see figure 4). Moreover, in our simulations there still exist multiple equilibria under IP-for-IP which shows that the multiplicity of equilibria under IP-for-IP is robust to the

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

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

introduction of asymmetry with respect to δ.

5 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 analyzed 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 is sufficiently high.

We show that the way IP is traded in the market for technology has an impact on the market for the creation of technology. Thus, this paper gives one (ex-ante orientated) explanation why cash might be a different currency than IP in the market for technology. This suggests that firms may influence R&D competition by modifying the terms of trade in the market for technology. However, in order to gain more insight in this topic, the model could be extended in various directions. One extension would be to take into account potential product market interactions between the two firms instead of assuming, as is done in this paper, that firms operate in distinct product markets.

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A Appendix

A.1 Derivation of equations (4) and (5)

The first order conditions for the maximization of firms' individual profits for project 1 are

$$\phi_{a_1} \equiv \frac{V}{4}(1-a_1)(4-(3-\delta)b_1)-1=0 \tag{6}$$

and

$$\phi_{b_1} \equiv \frac{V}{4}(1-b_1)(2-a_1)(1+\delta)-1=0\ . \tag{7}$$

Combining the two first order conditions and rearranging them using $c'(a_1) = (1-a_1)^{-1}$ and $c'(b_1) = (1-b_1)^{-1}$ yields equation (4). The same procedure applies to the derivation of equation (5) for project 2 (replacing a_1 with b_2 and b_1 with a_2).

A.2 Proof of proposition 1

First order conditions with respect to a_1 and b_1 are as given in (6) and (7). The unique solution (on the interval $[0,1]$) to these first order conditions is given by

$$a_1^{FT} = 1 - \frac{\sqrt{V^2(1+\delta)^4+32V(1+\delta)^2+64(1-\delta)^2}-V(1+\delta)^2-8(1-\delta)}{2V(1+\delta)^2} \tag{8}$$

and

$$b_1^{FT} = 1 - \frac{\sqrt{V^2(1+\delta)^4+32V(1+\delta)^2+64(1-\delta)^2}-V(1+\delta)^2+8(1-\delta)}{2V(1+\delta)(3-\delta)} \tag{9}$$

A non-negative success probability for firm B, b_1^{FT}, requires that $V \geq 3$. By symmetry, $a_2^{FT} = b_1^{FT}$ and $b_2^{FT} = a_1^{FT}$.

Consider next the joint probability of obtaining a patent in project 1, $1-(1-a_1^{FT})(1-b_1^{FT}) = a_1^{FT}+b_1^{FT}-a_1^{FT}b_1^{FT}$.[17] Total differentiation yields

$$\frac{d[a_1^{FT}+b_1^{FT}-a_1^{FT}b_1^{FT}]}{d\delta} = (1-b_1^{FT})\frac{da_1^{FT}}{d\delta}+(1-a_1^{FT})\frac{db_1^{FT}}{d\delta} \tag{10}$$

[17]By symmetry, the subsequent results also apply to project 2.

Let ϕ_{a_1x} (ϕ_{b_1x}) be the partial derivative of ϕ_{a_1} (ϕ_{b_1}) – as defined in (6) and (7) – with respect to x (and correspondingly for higher-order derivatives). Then

$$\frac{da_1^{FT}}{d\delta} = \frac{\phi_{a_1b_1}\phi_{b_1\delta} - \phi_{b_1b_1}\phi_{a_1\delta}}{\phi_{a_1a_1}\phi_{b_1b_1} - \phi_{a_1b_1}\phi_{b_1a_1}} \tag{11}$$

$$= \frac{\delta(1-a_1)(1-b_1)(2-a_1) + (1+\delta)(2-a_1)}{(4-(3-\delta)b_1)(2-a_1)(1+\delta) + \delta(1+\delta)(1-a_1)(1-b_1)} > 0 \tag{12}$$

$$\frac{db_1^{FT}}{d\delta} = \frac{\phi_{b_1a_1}\phi_{a_1\delta} - \phi_{a_1a_1}\phi_{b_1\delta}}{\phi_{a_1a_1}\phi_{b_1b_1} - \phi_{a_1b_1}\phi_{b_1a_1}} \tag{13}$$

$$= \frac{-(1+\delta)(1-a_1)(1-b_1) + (4-(3-\delta)b_1)(1-b_1)(1-a_1)}{(4-(3-\delta)b_1)(2-a_1)(1+\delta) + \delta(1+\delta)(1-a_1)(1-b_1)} \tag{14}$$

$$= \frac{(1-b_1)(4-(3-\delta)b_1 + 4(1-a_1)(1-b_1))}{(4-(3-\delta)b_1)(2-a_1)(1+\delta) + \delta(1+\delta)(1-a_1)(1-b_1)} > 0 \tag{15}$$

Hence, $\frac{d(a_1^{FT}+b_1^{FT}-a_1^{FT}b_1^{FT})}{d\delta} > 0$ implies that R&D investments are increasing in δ. 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: $1-(1-a_1^{FT}|_{\delta=0})(1-b_1^{FT}|_{\delta=0}) > 1-(1-a_1^{Coop})(1-b_1^{Coop})$ if

$$\frac{(\sqrt{V^2+32V+64}-V)^2-64}{12V^2} < \frac{1}{V} \tag{16}$$

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.

A.3 Proof of lemma 1

First order conditions for the IP-for-IP case are given by

$$\psi_{a_1} \equiv \frac{V}{4}(1-a_1)(4-b_1(2+(1-\delta)a_2(2-b_2))) - 1 = 0 \tag{17}$$

$$\psi_{a_2} \equiv \frac{V}{4}(1-a_2)(2-b_2)(2\delta+(1-\delta)b_1(2-a_1)) - 1 = 0 \tag{18}$$

$$\psi_{b_1} \equiv \frac{V}{4}(1-b_1)(2-a_1)(2\delta+(1-\delta)a_2(2-b_2)) - 1 = 0 \tag{19}$$

$$\psi_{b_2} \equiv \frac{V}{4}(1-b_2)(4-a_2(2+(1-\delta)b_1(2-a_1))) - 1 = 0 \tag{20}$$

For $\delta = 1$ these first order and those of the free trade case, (6) and (7) and symmetrically for a_2 and b_2, coincide.

A.4 Proof of proposition 2

In the following, we focus on symmetric equilibria and let $a_1 = b_2 = a$ and $b_1 = a_2 = b$ (that is, a represents the "home" project investment and b the investment for the project with limited commercialization ability). Thus, the first order conditions in (17) to (20) reduce to:

$$\psi_a \equiv \frac{V}{4}(1-a)(4-2b-(1-\delta)(2-a)b^2)-1=0 \tag{21}$$

$$\psi_b \equiv \frac{V}{4}(1-b)(2-a)(2\delta+(1-\delta)(2-a)b)-1=0 \tag{22}$$

As before, let ψ_{ax} (ψ_{bx}) be the partial derivative of ψ_a (ψ_b) with respect to x (and correspondingly for higher-order derivatives), and let $(.)|_{\psi_i}$ denote an analysis along the equilibrium locus ψ_i.

The (rather extensive) proof proceeds as follows (figure 5 illustrates the overall structure):

(i) Characterize the equilibrium locus ψ_a:
the set of equilibrium points is bounded by the curves for $\delta = 0$ and $\delta = 1$; for $\delta < 1$, the function $b(a)$ implied by ψ_a is hump-shaped with a maximum at $b \geq 1$; a solution with $(a, b) \in [0, 1]$ implies that $a \leq 1 - 1/V$.

(ii) Show that any equilibrium with $0 < b \leq 1$ implies overinvestment:
$b(a)|_{\psi_a}$ lies above the cooperative solution $b^{Coop}(a)$ implied by (3) for all $0 < b \leq 1$.

(iii) Characterize the equilibrium locus ψ_b:
the set of equilibrium points is bounded by the curves for $\delta = 0$ and $\delta = 1$; for $\delta < 1$, the function $a(b)$ implied by ψ_b is hump-shaped; a solution with $(a, b) \in [0, 1]$ implies that $b \leq 1 - 1/V$.

(iv) Show that there exists an equilibrium with $(a, b) \in (0, 1)^2$:
for lower values of a (b) and any $\delta \in [0, 1]$, the function $b(a)$ ($a(b)$) implied by ψ_a lies above (below) the one implied by ψ_b.

(v) Show that there is a critical δ where the cooperative solution applies.

(vi) Show that for δ below the critical level, there exist multiple equilibria with overinvestment:
for $\delta = 0$, $a(b)$ implied by ψ_b is lower than $a(b)$ implied by ψ_a.

(i) Properties of ψ_a: Consider the equilibrium condition (21):

- $b(a)|_{\psi_a}$ is (weakly) increasing in δ:

$$\left.\frac{db}{d\delta}\right|_{\psi_a} = -\frac{\psi_{a\delta}}{\psi_{ab}} \tag{23}$$

$$= \frac{b^2(2-a)}{2(1+(1-\delta)(2-a)b)} \geq 0 \tag{24}$$

- $b(a)|_{\psi_a}$ is increasing in V:

$$\left.\frac{db}{dV}\right|_{\psi_a} = -\frac{\psi_{aV}}{\psi_{ab}} \tag{25}$$

$$= \frac{2(1-b)+2(1-(1-\delta)b^2)+(1-\delta)ab^2}{2V(1+(1-\delta)(2-a)b)} > 0 \tag{26}$$

- For $\delta = 0$ and $V = 16$, $b(a)|_{\psi_a}$ has a maximum at $a = 1/2$ with $b(a = 1/2)|_{\psi_a} = 1$: For any $V > 1$ and $\delta \in [0,1)$

$$\left.\frac{db}{da}\right|_{\psi_a} = -\frac{\psi_{aa}}{\psi_{ab}} \tag{27}$$

$$= -\frac{4-2b-(1-\delta)(3-2a)b^2}{2(1-a)(1+(1-\delta)(2-a)b)} \tag{28}$$

which is equal to zero at $a^{max} \equiv \frac{3}{2} - \frac{2-b}{(1-\delta)b^2}$. This is a maximum:

$$\left.\frac{d^2b}{da^2}\right|_{\psi_a, a=a^{max}} = -\left.\frac{\psi_{aaa}}{\psi_{ab}}\right|_{a=a^{max}} \tag{29}$$

$$= -\frac{(1-\delta)b^2}{(1-a)(1+(1-\delta)(2-a)b)} < 0 \tag{30}$$

Now, inserting a^{max}, $V = 16$ and $\delta = 0$ into (21) yields two solutions for b and thus two maxima, one at $(a = 1/2, b = 1)$, the other outside the probability space $[0,1]^2$.

- For $\delta = 1$, $b(a)|_{\psi_a}$ is decreasing in a:

$$\left.\frac{db}{da}\right|_{\psi_a, \delta=1} = -\left.\frac{\psi_{aa}}{\psi_{ab}}\right|_{\delta=1} \tag{31}$$

$$= -\frac{2-b}{(1-a)} < 0 \tag{32}$$

because $\psi_a|_{a=0,\delta=1} = 0$ yields $b = 2(1-1/V) < 2$.

- $b(a)_{\psi_a}$ has a maximum support of $[0, 1-1/V]$ for $b \in [0,1]$: $\psi_a|_{b=0} = 0$ yields $a = 1 - 1/V$. As $b(a)_{\psi_a}$ is bounded from above by $b(a)_{\psi_a,\delta=1}$, any equilibrium has $a \leq 1 - 1/V$.

(ii) There is overinvestment for $b > 0$: The probability combinations of the cooperative solution are given by (3). It suffices to show that the equilibrium condition $\psi_a = 0$ with $\delta = 0$ (the lower boundary) implies that $b(a)_{\psi_a}$ lies above the function $b^{Coop}(a)$ implied by (3), except for $b = 0$ where the two coincide.

- For $b = 0$, conditions (3) (the cooperative solution) and $\psi_a|_{\delta=0} = 0$ (for the IP-for-IP case) both yield $a = 1 - 1/V$.

- For $V \geq 16$ and $a \in [0, 1/2]$, $b(a)_{\psi_a}$ is greater than $b^{Coop}(a)$: First note that, for $\delta = 0$, we have

$$\left.\frac{db}{da}\right|_{\psi_a,\delta=0,a=0} = -\frac{4 - 3b^2 - 2b}{2(1+2b)} \tag{33}$$

This slope is positive if $b > \frac{1}{3}(\sqrt{13} - 1)$, which is satisfied for $V \geq 16$:[18]

$$b(a=0)_{\psi_a,\delta=0} = \frac{1}{2}\left(\sqrt{1 + 8(1 - 1/V)} - 1\right) \tag{34}$$

is always greater than $\frac{1}{3}(\sqrt{13} - 1)$ for $V \geq 16$ (and even lower values). Hence, if $b(a=0)_{\psi_a,\delta=0} > 1 - 1/V$, then $b(a)_{\psi_a}$ is greater than $b^{Coop}(a)$ for all $a \in [0, 1/2]$. This requires

$$\sqrt{1 + 8(1 - 1/V)} + 2/V - 3 > 0 \tag{35}$$

As the left-hand term has a maximum at $V = 1.6$ and is positive there, we need to consider the limit:

$$\lim_{V \to \infty} \sqrt{1 + 8(1 - 1/V)} + 2/V - 3 = 0 \tag{36}$$

This confirms that $b(a=0)_{\psi_a,\delta=0} > 1 - 1/V$ for any V>1.

- For $V \geq 16$ and $a \in (1/2, 1 - 1/V)$, $b(a)_{\psi_a}$ is greater than $b^{Coop}(a)$: At $b = 0$ $b(a)_{\psi_a}$ and $b^{Coop}(a)$ coincide. Hence, if $b(a)_{\psi_a,\delta=0}$ has a lower slope

[18]Given the quadratic form of ψ_a, there is a second solution for b at $a = 0$ which is always negative and thus disregarded here.

coefficient (is steeper) over $a \in (1/2, 1-1/V)$ than $b^{Coop}(a)$, then it also lies above $b^{Coop}(a)$. By re-writing the conditions (3) and $\psi_a|_{\delta=0}$ in failure probabilities $\alpha \equiv 1-a$ and $\beta \equiv 1-b$ and taking logs, the slope requirement is then

$$\left.\frac{d\ln\beta}{d\ln\alpha}\right|_{\psi_a,\delta=0} < \frac{d\ln\beta^{Coop}}{d\ln\alpha} \tag{37}$$

$$\Leftrightarrow \quad \left.\frac{\alpha}{\beta}\frac{d\beta}{d\alpha}\right|_{\psi_a,\delta=0} < -1 \tag{38}$$

$$\Leftrightarrow \quad \frac{2+2\beta-(1-\beta)^2(1+2\alpha)}{2\beta+2\beta(1-\beta)(1+\alpha)} > 1 \tag{39}$$

which holds if $\alpha < \frac{1}{1-\beta} - \frac{1}{2}$ or $a > \frac{1}{2} - \frac{1}{b}$ which is satisfied for $V \geq 16$ because then $b(a)_{\psi_a} > 0$ over $a \in (1/2, 1-1/V)$.

(iii) Properties of ψ_b: Next, we can characterize equilibrium condition (22):

- $a(b)|_{\psi_b}$ is (weakly) increasing in δ:

$$\left.\frac{da}{d\delta}\right|_{\psi_b} = -\frac{\psi_{b\delta}}{\psi_{ba}} \tag{40}$$

$$= \frac{(2-a)(2-(2-a)b}{2((1-\delta)(2-a)b+\delta)} \geq 0 \tag{41}$$

- $a(b)|_{\psi_b}$ is increasing in V:

$$\left.\frac{da}{dV}\right|_{\psi_b} = -\frac{\psi_{bV}}{\psi_{ba}} \tag{42}$$

$$= \frac{(2-a)(2\delta+(1-\delta)(2-a)b)}{2V((1-\delta)(2-a)b+\delta)} > 0 \tag{43}$$

- For $\delta = 0$ and $b \in (0,1)$, $a(b)|_{\psi_b}$ has a maximum at $b = 1/2$:

$$\left.\frac{da}{db}\right|_{\psi_b,\delta=0} = -\left.\frac{\psi_{bb}}{\psi_{ba}}\right|_{\delta=0} \tag{44}$$

$$= \frac{(2-a)(1-2b)}{2b(1-b)} \tag{45}$$

is equal to zero for $b = 1/2$. This is a maximum as

$$\left.\frac{d^2a}{db^2}\right|_{\psi_b,\delta=0} = -\left.\frac{\psi_{bbb}\psi_{ba}-\psi_{bab}\psi_{bb}}{(\psi_{ba})^2}\right|_{\delta=0} \tag{46}$$

$$= -\frac{(2-a)(1+(1-2b)^2)}{2b^2(1-b)^2} < 0 \tag{47}$$

- For $\delta = 1$, $a(b)|_{\psi_b}$ is decreasing in b:

$$\left.\frac{da}{db}\right|_{\psi_b,\delta=1} = -\left.\frac{\psi_{bb}}{\psi_{ba}}\right|_{\delta=1} \tag{48}$$

$$= -\frac{2-a}{1-b} < 0 \tag{49}$$

- $b(a)|_{\psi_b}$ has a maximum support of $[0, 1-1/V]$ for $a \in [0,1]$: for $\delta = 1$, $\psi_b|_{a=0} = 0$ yields $b = 1 - 1/V$. As $a(b)|_{\psi_b}$ is bounded from above by $a(b)|_{\psi_b,\delta=1}$, any equilibrium has $b \leq 1 - 1/V$.

(iv) There exists an equilibrium with $b > 0$ (and overinvestment): We will show that, for V sufficiently large, the equilibrium loci always intersect at some interior point $(a,b) \in (0, 1-1/V)^2$:

- The equilibrium loci never intersect for $a \in [0, a^{max}]$: For $a = 0$, $b(a = 0)_{\psi_a,\delta=0} > 1 - \frac{1}{V}$, the upper boundary of $b(a)_{\psi_b}$ (see part (ii) of the proof). Hence, $b(a)_{\psi_a} > b(a)_{\psi_b}$ over the range $a \in [0, a^{max}]$.

- For $\delta = 0$, $V > 14$ and $b \in (0,1)$, the maximum of $a(b)|_{\psi_b}$ lies above $1-1/V$:

$$a(b = 1/2)|_{\psi_b,\delta=0} = 2 - \frac{4}{\sqrt{V}} \tag{50}$$

  which is greater than $1-1/V$ (the upper boundary of $a(b)|_{\psi_a}$) if $V > 7+4\sqrt{3}$. Hence, $V > 14$ is a sufficient condition for $a(b = 1/2)|_{\psi_b,\delta=0} > 1 - 1/V$.

These two features are sufficient for at leat one intersection of the two equilibrium loci with $(a,b) \in (1/V, 1)^2$ which by (ii) implies that there is overinvestment. This proofs part (i) of the proposition.

(v) For $\delta = \frac{2}{V+1}$ the cooperative solution is an equilibrium: For $b = 0$, $a(b)|_{\psi_a}$ always yields $a = 1 - 1/V$. This can only be an equilibrium if (22) also holds, which is true only for $\delta = \frac{2}{V+1}$.

(vi) For $\delta < \frac{2}{V+1}$ there exist multiple overinvestment equilibria: Because $a(b)|_{\psi_b}$ is increasing in δ (see (iii)) and has its maximum above $1-1/V$ (see (iv)), the two equilibrium loci have to intersect twice for $\delta \leq \frac{2}{V+1}$. For $\delta < \frac{2}{V+1}$, $b > 0$ for both equilibria which by (ii) implies that there is overinvestment in both equilibria. This concludes the proof of part (ii) of the proposition.

A.5 Proof of corollary 1

The results follow from comparative static analyses of the equilibrium conditions (21) and (22) for the IP-for-IP case and (6) and (7) for the free trade scenario, setting $a_1 = b_2 = a$ and $b_1 = a_2 = b$ in the latter two. Using the same notation as in the proof of proposition 2, we can define the following comparative static effects:

$$\frac{da^{FT}}{d\delta} = \frac{\phi_{ab}\phi_{b\delta} - \phi_{bb}\phi_{a\delta}}{\phi_{aa}\phi_{bb} - \phi_{ab}\phi_{ba}} \tag{51}$$

$$\frac{db^{FT}}{d\delta} = \frac{\phi_{ba}\phi_{a\delta} - \phi_{aa}\phi_{b\delta}}{\phi_{aa}\phi_{bb} - \phi_{ab}\phi_{ba}} \tag{52}$$

$$\frac{da^{IP}}{d\delta} = \frac{\psi_{ab}\psi_{b\delta} - \psi_{bb}\psi_{a\delta}}{\psi_{aa}\psi_{bb} - \psi_{ab}\psi_{ba}} \tag{53}$$

$$\frac{db^{IP}}{d\delta} = \frac{\psi_{ba}\psi_{a\delta} - \psi_{aa}\psi_{b\delta}}{\psi_{aa}\psi_{bb} - \psi_{ab}\psi_{ba}} \tag{54}$$

(i) then follows from (note that at $\delta = 1$, $a^{FT} = b^{FT} = a^{IP} = b^{IP} = a$)

$$\left.\frac{d[a^{FT} + b^{FT} - a^{FT}b^{FT}]}{d\delta}\right|_{\delta=1} = \left.(1-b)\frac{da^{FT}}{d\delta} + (1-a)\frac{db^{FT}}{d\delta}\right|_{\delta=1} = \frac{(1-a)^2}{3-2a} > 0 \tag{55}$$

$$\left.\frac{d[a^{IP} + b^{IP} - a^{IP}b^{IP}]}{d\delta}\right|_{\delta=1} = \left.(1-b)\frac{da^{IP}}{d\delta} + (1-a)\frac{db^{IP}}{d\delta}\right|_{\delta=1} = \frac{(1-a)^2 + (1-a)^5}{3-2a} > 0 \tag{56}$$

and

$$\left.\frac{d[a^{IP} + b^{IP} - a^{IP}b^{IP}]}{d\delta}\right|_{\delta=1} - \left.\frac{d[a^{FT} + b^{FT} - a^{FT}b^{FT}]}{d\delta}\right|_{\delta=1} = \frac{(1-a)^5}{3-2a} > 0\,. \tag{57}$$

(ii) follows from (note that at $\delta = 2/(V+1)$, $b = 0$ and $a = 1 - 1/V$)

$$\left.\frac{da^{IP}}{d\delta}\right|_{\delta=2/(V+1)} = \frac{1+V}{V^2-4V} > 0 \tag{58}$$

$$\left.\frac{db^{IP}}{d\delta}\right|_{\delta=2/(V+1)} = -\frac{2(1+V)}{V-4} < 0 \tag{59}$$

and

$$\left.\frac{d[a^{IP} + b^{IP} - a^{IP}b^{IP}]}{d\delta}\right|_{\delta=2/(V+1)} = -\frac{1+V}{V^2-4V} < 0 \tag{60}$$

where all signs hold for $V > 4$.

A.6 Proof of lemma 2

Inspection of table 1 shows that IP-for-IP is potentially costly in the following pre-trade allocations: $(B, \emptyset)$, $(\emptyset, A)$, (A, A) and (B, B). Unless $\delta = 1$, the differences in profits between the free trade and the IP-for-IP scenario are always strictly positive. Hence, for $\delta < 1$ IP-for-IP imposes no costs if the probability of either of the four allocations occurring is zero. This is true in a symmetric equilibrium (with $a_1 = b_2 = a$ and $b_1 = a_2 = b$) for $b = 0$ which is satisfied at $\delta = \frac{2}{V+1}$ (see the proof of proposition 2).

A.7 Proof of proposition 3

Given investments at the cooperative level (proposition 2) and zero cost of choosing IP-for-IP (lemma 2), choosing the IP-for-IP scenario and the low investment equilibrium levels of R&D yields the highest profits achievable for the two firms.

(ω_1, ω_2)	$p(\omega_1, \omega_2)$	$\pi_i(\omega_1, \omega_2)$	
		Free trade	IP-for-IP
$(\emptyset, \emptyset)$	$(1-a_1)(1-b_1)(1-a_2)(1-b_2)$	$\pi_A = 0$ $\pi_B = 0$	$\pi_A = 0$ $\pi_B = 0$
$(A, \emptyset)$	$(a_1(1-b_1)+\frac{1}{2}a_1b_1)(1-a_2)(1-b_2)$	$\pi_A = V$ $\pi_B = 0$	$\pi_A = V$ $\pi_B = 0$
$(B, \emptyset)$	$(b_1(1-a_1)+\frac{1}{2}b_1a_1)(1-a_2)(1-b_2)$	$\pi_A = \frac{1-\delta}{2}V$ $\pi_B = \frac{1+\delta}{2}V$	$\pi_A = 0$ $\pi_B = \delta V$
$(\emptyset, B)$	$(1-a_1)(1-b_1)(b_2(1-a_2)+\frac{1}{2}a_2b_2)$	$\pi_A = 0$ $\pi_B = V$	$\pi_A = 0$ $\pi_B = V$
$(\emptyset, A)$	$(1-a_1)(1-b_1)(a_2(1-b_2)+\frac{1}{2}a_2b_2)$	$\pi_A = \frac{1+\delta}{2}V$ $\pi_B = \frac{1-\delta}{2}V$	$\pi_A = \delta V$ $\pi_B = 0$
(A, A)	$(a_1(1-b_1)+\frac{1}{2}a_1b_1)(a_2(1-b_2)+\frac{1}{2}a_2b_2)$	$\pi_A = \frac{3+\delta}{2}V$ $\pi_B = \frac{1-\delta}{2}V$	$\pi_A = (1+\delta)V$ $\pi_B = 0$
(B, B)	$(b_1(1-a_1)+\frac{1}{2}b_1a_1)(b_2(1-a_2)+\frac{1}{2}a_2b_2)$	$\pi_A = \frac{1-\delta}{2}V$ $\pi_B = \frac{3+\delta}{2}V$	$\pi_A = 0$ $\pi_B = (1+\delta)V$
(B, A)	$(a_2(1-b_2)+\frac{1}{2}a_2b_2)(b_1(1-a_1)+\frac{1}{2}b_1a_1)$	$\pi_A = V$ $\pi_B = V$	$\pi_A = V$ $\pi_B = V$
(A, B)	$(a_1(1-b_1)+\frac{1}{2}a_1b_1)(b_2(1-a_2)+\frac{1}{2}a_2b_2)$	$\pi_A = V$ $\pi_B = V$	$\pi_A = V$ $\pi_B = V$

Table 1: Patent allocations and payoffs

(ω_1, ω_2)	Base Model $\pi_i(\omega_1, \omega_2)$		Feature Complementarity $\pi_i(\omega_1, \omega_2)$		Asymmetric Firms $\pi_i(\omega_1, \omega_2)$	
	Free trade	IP-for-IP	Free trade	IP-for-IP	Free trade	IP-for-IP
$(\emptyset, \emptyset)$	$\pi_A = 0$ $\pi_B = 0$	$\pi_A = 0$ $\pi_B = 0$	$\pi_A = 0$ $\pi_B = 0$	$\pi_A = 0$ $\pi_B = 0$	$\pi_A = 0$ $\pi_B = 0$	$\pi_A = 0$ $\pi_B = 0$
$(A, \emptyset)$	$\pi_A = V$ $\pi_B = 0$	$\pi_A = V$ $\pi_B = 0$	$\pi_A = V$ $\pi_B = 0$	$\pi_A = V$ $\pi_B = 0$	$\pi_A = V$ $\pi_B = 0$	$\pi_A = V$ $\pi_B = 0$
$(B, \emptyset)$	$\pi_A = \frac{1-\delta}{2}V$ $\pi_B = \frac{1+\delta}{2}V$	$\pi_A = 0$ $\pi_B = \delta V$	$\pi_A = \frac{1-\delta}{2}V$ $\pi_B = \frac{1+\delta}{2}V$	$\pi_A = 0$ $\pi_B = \delta V$	$\pi_A = \frac{1}{2}V$ $\pi_B = \frac{1}{2}V$	$\pi_A = 0$ $\pi_B = 0$
$(\emptyset, B)$	$\pi_A = 0$ $\pi_B = V$	$\pi_A = 0$ $\pi_B = V$	$\pi_A = 0$ $\pi_B = V$	$\pi_A = 0$ $\pi_B = V$	$\pi_A = 0$ $\pi_B = V$	$\pi_A = 0$ $\pi_B = V$
$(\emptyset, A)$	$\pi_A = \frac{1+\delta}{2}V$ $\pi_B = \frac{1-\delta}{2}V$	$\pi_A = \delta V$ $\pi_B = 0$	$\pi_A = \frac{1+\delta}{2}V$ $\pi_B = \frac{1-\delta}{2}V$	$\pi_A = \delta V$ $\pi_B = 0$	$\pi_A = \frac{1+\delta}{2}V$ $\pi_B = \frac{1-\delta}{2}V$	$\pi_A = \delta V$ $\pi_B = 0$
(A, A)	$\pi_A = \frac{3+\delta}{2}V$ $\pi_B = \frac{1-\delta}{2}V$	$\pi_A = (1+\delta)V$ $\pi_B = 0$	$\pi_A = \frac{3+\delta}{2}\gamma V$ $\pi_B = \frac{1-\delta}{2}\gamma V$	$\pi_A = (1+\delta)\gamma V$ $\pi_B = 0$	$\pi_A = \frac{3+\delta}{2}V$ $\pi_B = \frac{1-\delta}{2}V$	$\pi_A = (1-\delta)V$ $\pi_B = 0$
(B, B)	$\pi_A = \frac{1-\delta}{2}V$ $\pi_B = \frac{3+\delta}{2}V$	$\pi_A = 0$ $\pi_B = (1+\delta)V$	$\pi_A = \frac{1-\delta}{2}\gamma V$ $\pi_B = \frac{3+\delta}{2}\gamma V$	$\pi_A = 0$ $\pi_B = (1+\delta)\gamma V$	$\pi_A = \frac{1}{2}V$ $\pi_B = \frac{3}{2}V$	$\pi_A = 0$ $\pi_B = V$
(B, A)	$\pi_A = V$ $\pi_B = V$	$\pi_A = V$ $\pi_B = V$	$\pi_A = \gamma V$ $\pi_B = \gamma V$	$\pi_A = \gamma V$ $\pi_B = \gamma V$	$\pi_A = (1+\frac{\delta}{2})V$ $\pi_B = (1-\frac{\delta}{2})V$	$\pi_A = V$ $\pi_B = V$
(A, B)	$\pi_A = V$ $\pi_B = V$	$\pi_A = V$ $\pi_B = V$	$\pi_A = \gamma V$ $\pi_B = \gamma V$	$\pi_A = \gamma V$ $\pi_B = \gamma V$	$\pi_A = V$ $\pi_B = V$	$\pi_A = V$ $\pi_B = V$

Table 2: Patent allocations and alternative payoffs

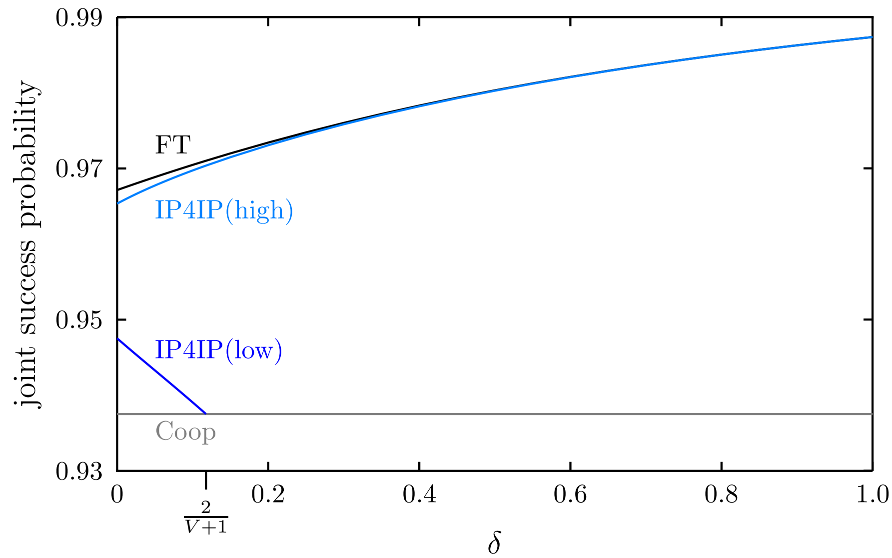

Figure 1: R&D decisions: joint probabilities ($V = 16$)

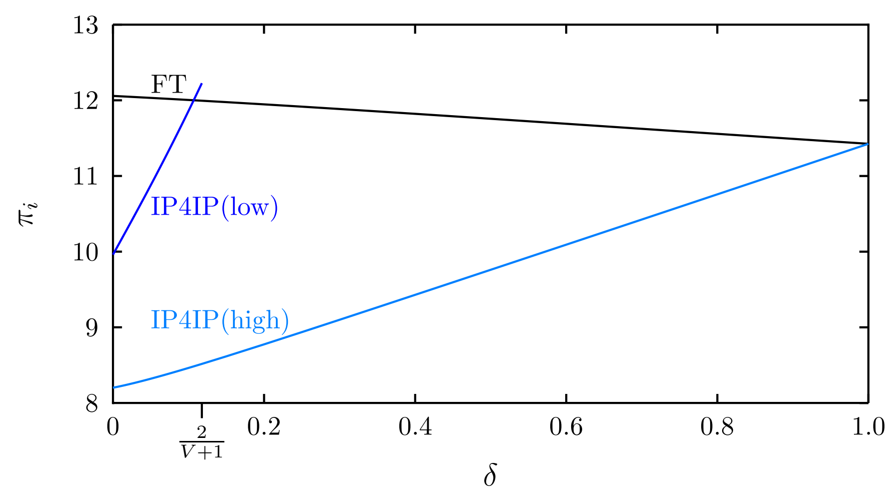

Figure 2: Expected profits ($V = 16$)

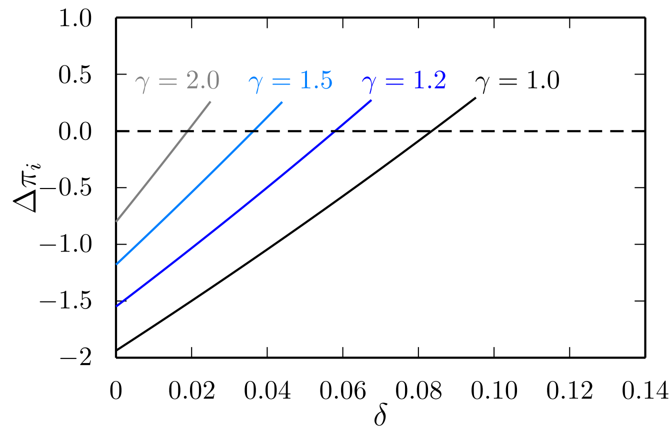

Figure 3: Feature complementarity: Profitability of IP-for-IP strategy ($V = 20$)

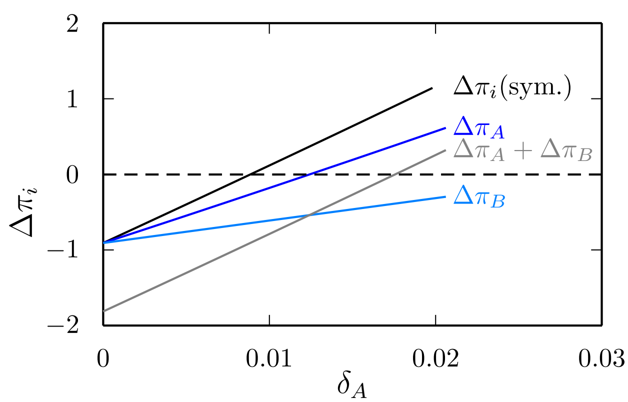

Figure 4: Asymmetric firms: Profitability of IP-for-IP strategy ($V = 100$)

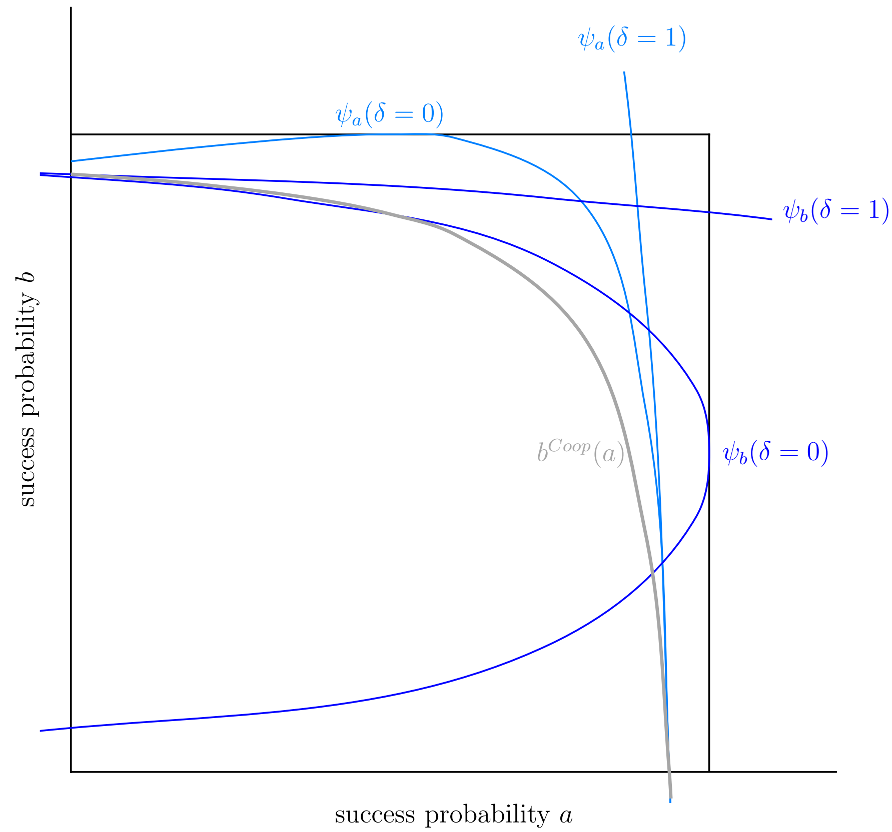

Figure 5: Sketch of proof for proposition 2