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. 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 budget 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. 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

[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.

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 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,

[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).

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 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.

[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.

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

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 (see 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 restrict the analysis to symmetric Nash equilibria.

We assume that firms are able to commit to their 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 assume that firms are able to restrict their ability to change their initial decision. This might be achieved by posting a 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] 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

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

[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.

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

The unconditional success probability of firm A for project j ($j = 1, 2$) is $1 - e^{-a_j}$ where $a_j \geq 0$ represents the R&D expenditures of firm A on project j. Likewise, firm B is successful on project j with probability $1 - e^{-b_j}$ with $b_j \geq 0$ being the R&D expenditures of firm B on project 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 type of success probability implies that the overall success probability on a certain project does only depend on the total level of R&D expenditures but not on its allocation over firms.

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

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

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.[8]

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

$$E[\pi_A + \pi_B] \quad = \quad V(2 - e^{-(a_1+b_1)} - e^{-(a_2+b_2)}) - a_1 - a_2 - b_1 - b_2. \qquad (2)$$

This is maximized at $a_1 + b_1 = a_2 + b_2 = \ln V$ with $V \geq 1$ to ensure non-negative investment levels.

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 in the symmetric equilibrium $(a_1 = b_2, a_2 = b_1)$ the following relations[9]

$$e^{a_1} \quad = \quad e^{b_1} + 2\frac{(1-\delta)}{(1+\delta)} \qquad (3)$$

$$e^{b_2} \quad = \quad e^{a_2} + 2\frac{(1-\delta)}{(1+\delta)}, \qquad (4)$$

where $\frac{(1-\delta)}{(1+\delta)} \in [0, 1]$. 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 $V \geq 3$. Under free trade, the symmetric equilibrium regarding firms' R&D expenditures is unique and characterized by overinvestment compared to the cooperative solution. The level of overinvestment is increasing in δ.*

[8] We consider asymmetric valuations in section 4.

[9] 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. Again, we are interested in the symmetric equilibria of R&D competition under an IP-for-IP regime, i.e. in 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 irrelevant 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 expenditures. 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 expenditure equilibrium") exists over the full range of δ whereas the second equilibrium ("low expenditure equilibrium") does not exist if $\delta > \frac{2}{V+1}$.[10] At $\delta = \frac{2}{V+1}$ the low expenditure 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) invests $\ln V$ (zero) in project 1 and zero ($\ln V$) in project 2.

Corollary 1 *(i) Let $\delta = 1$. Then, a marginal reduction in δ lowers firms' total R&D expenditures in both the free trade scenario and under IP-for-IP. However, the decrease in total R&D expenditures is larger under IP-for-IP than under free trade. (ii) Consider the low expenditure IP-for-IP equilibrium at $\delta = \frac{2}{V+1}$ (where $a_1 = b_2 = \ln V$ 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 expenditures.*

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 expenditures under IP-for-IP than under free trade suggesting that firms' total investment 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 expenditures inversely related to δ in the low expenditure equilibrium. Figure 1 presents again the results derived so far. It shows the R&D expenditures per firm in the symmetric equilibria for $V = 16$. 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-expenditure equilibrium). Both are characterized by lower

[10] 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 productivity of R&D when expenditures are zero. If the success probability is adjusted such that marginal productivity is infinite at zero expenditures, this third equilibrium does not exist any more, while the other two prevail. However, due to tractability of the analysis, the finite marginal productivity form is used in the paper.

investments than under free trade. At $\delta = 2/17$ the low expenditure 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 forgone gains from trade 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 expenditure equilibrium and zero costs in the low expenditure equilibrium. There exists no further value of δ where the costs of IP-for-IP are zero in either of the two equilibria.*

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-expenditure 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-expenditure 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 expenditure 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 $\delta \in (\delta_o, \frac{2}{V+1}]$ IP-for-IP is the most profitable strategy.[11] Hence, there is a parameter range for δ where IP-for-IP and the low expenditure

[11] Numerical calculations show that for higher values of V, δ_o is negative.

equilibrium form a subgame perfect equilibrium. (2) As the high expenditure equilibrium produces lower profits than either the free trade scenario (except for $\delta = 1$) or the low expenditure equilibrium, we can also conclude that choosing free trade and corresponding R&D expenditure levels is a subgame perfect equilibrium for all levels of δ. (3) Unless there exists an asymmetric equilibrium in the free trade scenario which yields even lower profits than the high expenditure equilibrium under IP-for-IP, the choice of the latter is not a subgame perfect equilibrium, as it would be dominated by the free trade equilibrium.[12] 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 expenditure 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 expenditure IP-for-IP equilibrium yields higher profits than free trade, the following strategy supports restricting oneself to IP-for-IP and the corresponding low expenditure equilibrium investments for discount factors sufficiently close to one: each player invests according to the low expenditure equilibrium and only suggests trade if it is reciprocal (barter). Players continue to do so in all following repetitions unless 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 two extensions to our model that 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 full sale of IP. Second, we introduce firm heterogeneity by allowing the two firms to differ in their commercialization abilities. Both extensions are solved

[12]IP-for-IP and the high expenditure equilibrium form a Nash equilibrium of the complete game only if choice of free trade produces even lower profits. This violates the requirements of subgame perfection unless the above-mentioned asymmetric equilibrium exists. We were unable to find such an equilibrium in our simulations.

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.[13] 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.

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 expenditure equilibrium investments) 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 term 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

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

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.[14] In contrast, firm A still obtains a positive value from patent 2 when trade is not possible.[15] 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 implying that the multiplicity of equilibria under IP-for-IP is robust to the introduction of asymmetry with respect to δ.

5 Concluding Remarks

The model in this paper argues that the type of "currency" used in technology transactions may have an impact on R&D competition between firms. In the simplest set-up, the model has two firms allocating 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 have analyzed the effects that arise from a trade restricting strategy which restrains firms from using cash when trading technology. The model has shown 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 has shown that IP-for-IP can be a profitable strategy as long as the difference between firms' commercialization abilities is sufficiently high.

This model has shown that the way IP is traded in the market for technology has an impact on the market for the creation of technology. Thus, it gives one (ex-ante orientated) explanation why cash might be a different currency than IP in the

[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.

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 straightforward 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 (3) and (4)

The first order conditions for the maximization of firms' individual profits under the assumption of symmetry ($a_2 = b_1, b_2 = a_1$) for project 1 are

$$\frac{V}{4}(e^{-a_1}((1+\delta)+(3-\delta)e^{-b_1}))-1=0 \tag{5}$$

and

$$\frac{V}{4}\,(\delta+1)\,e^{-b_1}(1+e^{-a_1})-1=0\,. \tag{6}$$

The combination of these two first order conditions yields equation (3). The same procedure applies to the derivation of equation (4).

A.2 Proof of proposition 1

First order conditions with respect to a_1 and b_1 can be expressed as

$$\frac{1}{e^{a_1}}=\frac{4}{(1+\delta)V}-\frac{(3-\delta)}{(1+\delta)}\frac{1}{e^{a_1+b_1}} \tag{7}$$

and

$$\frac{1}{e^{b_1}}=\frac{4}{(1+\delta)\,V}-\frac{1}{e^{a_1+b_1}}\ , \tag{8}$$

respectively. The unique defined mutual solution to these first order conditions is given by

$$a_1=\ln\frac{V(1+\delta)^2+8(1-\delta)+\sqrt{V^2(1+\delta)^4+32V\,(1+\delta)^2+64(1-\delta)^2}}{8(1+\delta)} \tag{9}$$

and

$$b_1=\ln\frac{V(1+\delta)^2-8(1-\delta)+\sqrt{V^2(1+\delta)^4+32V\,(1+\delta)^2+64(1-\delta)^2}}{8(1+\delta)}\ . \tag{10}$$

In order to ensure non-negative individual investment levels it is required that $V \geq 3$. The sum of non-cooperative investments is thus

$$a_1+b_1=\ln\frac{(V(1+\delta)^2+\sqrt{V^2(1+\delta)^4+32V\,(1+\delta)^2+64(1-\delta)^2})^2-64(1-\delta)^2}{64(1+\delta)^2} \tag{11}$$

which is greater than $\ln V$ for $V \geq 3$ and increasing in δ.

A.3 Proof of lemma 1

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

$$a_1 \;:\; e^{-a_1}\frac{1}{2}(1+e^{-b_1}-\frac{1}{2}(1-\delta)\left(1-e^{-b_1}\right)\left(1-e^{-a_2}\right)(1+e^{-b_2}))=\frac{1}{V} \quad (12)$$

$$a_2 \;:\; e^{-a_2}\frac{1}{4}\left(1+e^{-b_2}\right)(2\delta+(1-\delta)\left(1-e^{-b_1}\right)(1+e^{-a_1}))=\frac{1}{V} \quad (13)$$

$$b_1 \;:\; e^{-b_1}\frac{1}{4}\left(1+e^{-a_1}\right)(2\delta+(1-\delta)\left(1-e^{-a_2}\right)(1+e^{-b_2}))=\frac{1}{V} \quad (14)$$

$$b_2 \;:\; e^{-b_2}\frac{1}{2}(1+e^{-a_2}-\frac{1}{2}(1-\delta)\left(1-e^{-a_2}\right)\left(1-e^{-b_1}\right)(1+e^{-a_1}))=\frac{1}{V} \quad (15)$$

If $\delta=1$ the these first order coincide with those under free trade and reduce to

$$a_1 \;:\; e^{-a_1}\frac{1}{2}(1+e^{-b_1})=\frac{1}{V} \quad (16)$$

$$a_2 \;:\; e^{-a_2}\frac{1}{2}\left(1+e^{-b_2}\right)=\frac{1}{V} \quad (17)$$

$$b_1 \;:\; e^{-b_1}\frac{1}{2}\left(1+e^{-a_1}\right)=\frac{1}{V} \quad (18)$$

$$b_2 \;:\; e^{-b_2}\frac{1}{2}(1+e^{-a_2})=\frac{1}{V}. \quad (19)$$

A.4 Proof of proposition 2

By focussing on symmetric equilibria, the first order conditions in (12) to (15) reduce to (substitute $a_2=b_1$ and $b_2=a_1$):

$$e^{-a_1}\frac{V}{2}(1+e^{-b_1}-\frac{1}{2}(1-\delta)\left(1-e^{-b_1}\right)^2(1+e^{-a_1}))-1=0 \quad (20)$$

$$e^{-b_1}\frac{V}{4}\left(1+e^{-a_1}\right)(2\delta+(1-\delta)\left(1-e^{-b_1}\right)(1+e^{-a_1}))-1=0 \quad (21)$$

In what follows, we will mostly analyze these equilibrium loci in terms of the "failure probabilities" $a\equiv e^{-a_1}\le 1$ and $b\equiv e^{-b_1}\le 1$:

$$\psi_a \;\equiv\; a\frac{V}{2}(1+b-\frac{1}{2}(1-\delta)(1-b)^2(1+a))-1=0 \quad (22)$$

$$\psi_b \;\equiv\; b\frac{V}{4}(1+a)(2\delta+(1-\delta)(1-b)(1+a))-1=0 \quad (23)$$

The proof then proceeds in four steps: (a) characterize the two equilibrium loci; (b) show that the equilibrium loci always intersect for some $b<1$; (c) show that any equilibrium with $b<1$ implies overinvestment; (d) show that there is a critical delta where the cooperative solution applies. (e) show that for δ below the critical level, there exist additional equilibria with overinvestment.

(a) Characterization of equilibrium loci: 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.

Then (22) defines an equilibrium locus with the following properties:

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

$$\left.\frac{db}{d\delta}\right|_{\psi_a} = -\frac{\psi_{a\delta}}{\psi_{ab}} \tag{24}$$

$$= -\frac{\frac{V}{4}a(1-b)^2(1+a)}{\frac{V}{2}a(1+(1-\delta)(1-b)(1+a))} \leq 0 \tag{25}$$

- For $\delta = 0$ and $b < 1$, $b(a)|_{\psi_a}$ has a minimum at $a = \frac{1+b}{(1-b)^2} - \frac{1}{2}$:

$$\left.\frac{db}{da}\right|_{\psi_a,\delta=0} = -\left.\frac{\psi_{aa}}{\psi_{ab}}\right|_{\delta=0} \tag{26}$$

$$= -\frac{\frac{V}{2}(1+b-(1-b)^2(\frac{1}{2}+a))}{\frac{V}{2}a(1+(1-b)(1+a))} \tag{27}$$

which is equal to zero at $a^{min} \equiv \frac{1+b}{(1-b)^2} - \frac{1}{2}$. This is a minimum:

$$\left.\frac{d^2b}{da^2}\right|_{\psi_a,\delta=0,a=a^{min}} = -\left.\frac{\psi_{aaa}}{\psi_{ab}}\right|_{\delta=0,a=a^{min}} > 0 \tag{28}$$

as $\psi_{aaa} = -(1-b)^2V/2 < 0$.

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

$$\left.\frac{db}{da}\right|_{\psi_a,\delta=1} = -\left.\frac{\psi_{aa}}{\psi_{ab}}\right|_{\delta=1} \tag{29}$$

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

- $a(b)_{\psi_a}$ has a lower boundary at $1/V$ for $b \in [0,1]$: for $\delta = 1$, inserting the boundary yields $b(a = 1/V)|_{\psi_a,\delta=1} = 1$. As $b(a)|_{\psi_a}$ is (weakly) decreasing in δ, $a(b)|_{\psi_a} \geq 1/V$ for any $\delta \in [0,1]$.

In sum, the function $b(a)$ defined by (22) has a maximum support of $[1/V, 1]$, has a lower boundary for $\delta = 1$, has an upper boundary for $\delta = 0$, is decreasing in a for $\delta = 1$ and is u-shaped for $\delta = 0$.

Next, we can characterize the equilibrium locus defined by (23):

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

$$\left.\frac{da}{d\delta}\right|_{\psi_b} = -\frac{\psi_{b\delta}}{\psi_{ba}} \tag{31}$$

$$= -\frac{b\frac{V}{4}(1+a)(2-(1+a)(1-b))}{b\frac{V}{2}(\delta+(1-\delta)(1-b)(1+a))} < 0 \tag{32}$$

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

$$\left.\frac{da}{db}\right|_{\psi_b,\delta=0} = -\left.\frac{\psi_{bb}}{\psi_{ba}}\right|_{\delta=0} \tag{33}$$

$$= -\frac{\frac{V}{4}(1+a)^2(1-2b)}{b\frac{V}{2}(1-b)(1+a)} \tag{34}$$

is equal to zero for $b = 1/2$. To confirm that this is a minimum, we need to show that

$$\left.\frac{d^2a}{db^2}\right|_{\psi_b,\delta=0,b=1/2} = -\left.\frac{\psi_{bbb}\psi_{ba} - \psi_{bab}\psi_{bb}}{(\psi_{ba})^2}\right|_{\delta=0,b=1/2} > 0 \tag{35}$$

which is true because

$$-(\psi_{bbb}\psi_{ba} - \psi_{bab}\psi_{bb})|_{\delta=0,b=1/2} = \frac{V^2}{16}(1+a)^3 > 0 \tag{36}$$

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

$$\left.\frac{da}{db}\right|_{\psi_b,\delta=1} = -\left.\frac{\psi_{bb}}{\psi_{ba}}\right|_{\delta=1} \tag{37}$$

$$= -\frac{\frac{V}{2}(1+a)}{\frac{V}{2}b} < 0 \tag{38}$$

- $b(a)|_{\psi_b}$ has a lower boundary at $1/V$ for $a \in [0,1]$: for $\delta = 1$, inserting the boundary yields $a(b = 1/V)|_{\psi_b\delta=1} = 1$. As $a(b)|_{\psi_b}$ is decreasing in δ and in b, any $\delta < 1$ implies $b(a)|_{\psi_b} > 1/V$.

In sum, the function $a(b)$ defined by (23) has a maximum support of $[1/V, 1]$, has a lower boundary for $\delta = 1$, has an upper boundary for $\delta = 0$, is decreasing in b for $\delta = 1$ and is u-shaped for $\delta = 0$.

(b) There exists always an equilibrium with $b < 1$: We will next show that, for V sufficiently large, the equilibrium loci always intersect at some interior point $(a,b) \in (1/V, 1)^2$.

- The equilibrium loci never intersect for $a \in [a^{min}, 1]$: For $a = 1$, $b(a = 1)_{\psi_a,\delta=0} = \frac{3}{2} \pm \frac{1}{2}\sqrt{9 - 8/V}$; the (relevant) lower solution always lies below $1/V$, which is the lower boundary of $b(a)_{\psi_b}$: $\frac{3}{2} - \frac{1}{2}\sqrt{9-8/V} - \frac{1}{V}$ is increasing in V and approaches zero asymptotically (from below).

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

$$a(b = 1/2)|_{\psi_b,\delta=0} = \frac{4}{\sqrt{V}} - 1 \tag{39}$$

which is lower than $1/V$ if $V > 7 + 4\sqrt{3}$. Hence, $V > 14$ is a sufficient condition for $a(b = 1/2)|_{\psi_b,\delta=0} < 1/V$.

These two features are sufficient for an intersection of the two equilibrium loci with $(a,b) \in (1/V, 1)^2$.

(c) For all equilibria with $b \in [1/V, 1)$, there is overinvestment: Overinvestment relative to the cooperative solution exists if $a_1 + b_1 > \ln V$. Along the equilibrium locus defined by (20), the cooperative level of investment is reached for $b_1 = 0$. If, for any $b_1 \in [0, \ln V]$, the implied function of a_1 (at its lower bound, ie for $\delta = 0$) decreases by less than one, then there is overinvestment for any $b_1 > 0$. Totally differentiating (20) yields (along the equilibrium locus):

$$\frac{da_1}{db_1} = -\frac{-e^{-a1}e^{-b1}\frac{V}{2}(1 + (1 - e^{-b1})(1 + e^{-a1}))}{-e^{-a1}\frac{V}{2}(1 + e^{-b1} - (1 - e^{-b1})^2(\frac{1}{2} + e^{-a1}))} \tag{40}$$

The absolute value of this slope has to be less than one, which requires (replacing again e^{-a1} with a and e^{-b1} with b)

$$b(1 + (1 - b)(1 + a)) < 1 + b - (1 - b)^2(\frac{1}{2} + a) \ , \tag{41}$$

or

$$a < \frac{1 + b^2}{2(1 - b)} \tag{42}$$

Note that for $V \geq 16$, the equilibrium a is bounded from above at $a = 1/2$: $a(b = 0)_{\psi_a,\delta=0} = \frac{1}{2}(1 \pm \sqrt{1 - 16/V})$, where the lower solution applies as it lies below the minimum of $a(b)_{\psi_a,\delta=0}$. Hence, (42) is always fulfilled if $\frac{1+b^2}{2(1-b)} > \frac{1}{2}$, which is true for all $b > 0$. This proofs that there is overinvestment for any $b_1 > 0$ and concludes the proof of (i).

(d) For $\delta = \frac{2}{V+1}$ the cooperative solution is an equilibrium: For $b = 1$, $a(b)|_{\psi_a}$ always yields $a = 1/V$. This can only be an equilibrium if (23) also holds, which is true only for $\delta = \frac{2}{V+1}$.

(e) For $\delta < \frac{2}{V+1}$ there exist multiple overinvestment equilibria: Because $a(b)|_{\psi_b}$ is decreasing in δ (see (a)) and has its minimum below $1/V$ (see (b)), the two equilibrium loci have to intersect twice for $\delta \leq \frac{2}{V+1}$. For $\delta < \frac{2}{V+1}$, $b < 1$ for both equilibria. Given the argument in (d), the latter implies that there is overinvestment in both equilibria. This concludes the proof of (ii).

A.5 Proof of corollary 1

The results follow from comparative static analyses of the equilibrium conditions (22) and (23) for the IP-for-IP case and (5) and (6) for the free trade scenario. In order to simplify the exposition, the analysis is done in "failure probabilities" $a \equiv e^{-a_1} \leq 1$ and $b \equiv e^{-b_1} \leq 1$ with superscript IP and FT indicating the two scenarios, respectively. Re-writing (5) and (6) yields

$$\phi_a \equiv \frac{V}{4}a(1+\delta+(3-\delta)b)-1=0 \tag{43}$$

$$\phi_b \equiv \frac{V}{4}(1+\delta)b(1+a)-1=0\,. \tag{44}$$

Using the same notation as in the proof of proposition 2, we can define the following comparative static effects:

$$\frac{da^{FT}}{d\delta} = \frac{\phi_{ab}\phi_{b\delta}-\phi_{bb}\phi_{a\delta}}{\phi_{aa}\phi_{bb}-\phi_{ab}\phi_{ba}} \tag{45}$$

$$\frac{db^{FT}}{d\delta} = \frac{\phi_{ba}\phi_{a\delta}-\phi_{aa}\phi_{b\delta}}{\phi_{aa}\phi_{bb}-\phi_{ab}\phi_{ba}} \tag{46}$$

$$\frac{da^{IP}}{d\delta} = \frac{\psi_{ab}\psi_{b\delta}-\psi_{bb}\psi_{a\delta}}{\psi_{aa}\psi_{bb}-\psi_{ab}\psi_{ba}} \tag{47}$$

$$\frac{db^{IP}}{d\delta} = \frac{\psi_{ba}\psi_{a\delta}-\psi_{aa}\psi_{b\delta}}{\psi_{aa}\psi_{bb}-\psi_{ab}\psi_{ba}} \tag{48}$$

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

$$\left.\frac{d[a^{FT}b^{FT}]}{d\delta}\right|_{\delta=1} = \left. b\frac{da^{FT}}{d\delta}+a\frac{db^{FT}}{d\delta}\right|_{\delta=1} = -\frac{a^2}{1+2a}<0 \tag{49}$$

$$\left.\frac{d[a^{IP}b^{IP}]}{d\delta}\right|_{\delta=1} = \left. b\frac{da^{IP}}{d\delta}+a\frac{db^{IP}}{d\delta}\right|_{\delta=1} = -\frac{a^2+a^5}{1+2a}<0 \tag{50}$$

and

$$\left.\frac{d[a^{IP}b^{IP}]}{d\delta}\right|_{\delta=1} - \left.\frac{d[a^{FT}b^{FT}]}{d\delta}\right|_{\delta=1} = -\frac{a^5}{1+2a}<0 \tag{51}$$

(ii) follows from (note that at $\delta=2/(V+1)$, $b=1$ and $a=1/V$ in the cooperative equilibrium)

$$\left.\frac{da^{IP}}{d\delta}\right|_{\delta=2/(V+1)} = \frac{1+V}{4V-V^2}<0 \tag{52}$$

$$\left.\frac{db^{IP}}{d\delta}\right|_{\delta=2/(V+1)} = \frac{2(1+V)}{V-4}>0 \tag{53}$$

and

$$\left.\frac{d[a^{IP}b^{IP}]}{d\delta}\right|_{\delta=2/(V+1)} = \frac{1+V}{V^2-4V}>0 \tag{54}$$

where all signs hold for $V>4$.

A.6 Proof of lemma 2

Firm A's expected costs of IP-for-IP in the symmetric case are

$$\frac{(1-\delta)}{4} V \alpha_B \left(2-\alpha_A\right)\left(2-2\alpha_B+\alpha_A\alpha_B\right) \tag{55}$$

where $\alpha_A \equiv 1-e^{-a_1}$ and $\alpha_B \equiv 1-e^{-b_1}$. These costs can only become zero if (i) $\delta = 1$, or (ii) $\alpha_B = 0$ ($\Leftrightarrow b_1 = 0$). The latter case holds if $\delta = \frac{2}{V+1}$. The term $(2-2\alpha_B+\alpha_A\alpha_B)$ cannot become zero as $\alpha_B < 1$ but $\alpha_A \geq 0$.

A.7 Proof of proposition 3

Given the investment levels at the cooperative level (proposition 2) and zero cost of choosing IP-for-IP (lemma 2) choice of the IP-for-IP scenario and the low expenditure equilibrium levels of R&D spending 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
$(\emptyset, \emptyset)$	$(e^{-a_1}e^{-b_1}) \cdot (e^{-a_2}e^{-b_2})$	$\pi_A = 0$ $\pi_B = 0$	$\pi_A = 0$ $\pi_B = 0$
$(A, \emptyset)$	$[(1-e^{-a_1})(e^{-b_1}) + \frac{1}{2}(1-e^{-a_1})(1-e^{-b_1})] \cdot$ $(e^{-a_2}e^{-b_2})$	$\pi_A = V$ $\pi_B = 0$	$\pi_A = V$ $\pi_B = 0$
$(B, \emptyset)$	$[(1-e^{-b_1})(e^{-a_1}) + \frac{1}{2}(1-e^{-a_1})(1-e^{-b_1})] \cdot$ $(e^{-a_2}e^{-b_2})$	$\pi_A = \frac{1-\delta}{2}V$ $\pi_B = \frac{1+\delta}{2}V$	$\pi_A = 0$ $\pi_B = \delta V$
$(\emptyset, B)$	$[(1-e^{-b_2})(e^{-a_2}) + \frac{1}{2}(1-e^{-b_2})(1-e^{-a_2})] \cdot$ $(e^{-a_1}e^{-b_1})$	$\pi_A = 0$ $\pi_B = V$	$\pi_A = 0$ $\pi_B = V$
$(\emptyset, A)$	$[(1-e^{-a_2})(e^{-b_2}) + \frac{1}{2}(1-e^{-b_2})(1-e^{-a_2})] \cdot$ $(e^{-a_1}e^{-b_1})$	$\pi_A = \frac{1+\delta}{2}V$ $\pi_B = \frac{1-\delta}{2}V$	$\pi_A = \delta V$ $\pi_B = 0$
(A, A)	$[(1-e^{-a_1})(e^{-b_1}) + \frac{1}{2}(1-e^{-a_1})(1-e^{-b_1})] \cdot$ $\left[(1-e^{-a_2})(e^{-b_2}) + \frac{1}{2}(1-e^{-a_2})(1-e^{-b_2})\right]$	$\pi_A = \frac{3+\delta}{2}V$ $\pi_B = \frac{1-\delta}{2}V$	$\pi_A = (1+\delta)V$ $\pi_B = 0$
(B, B)	$[(1-e^{-b_1})(e^{-a_1}) + \frac{1}{2}(1-e^{-a_1})(1-e^{-b_1})] \cdot$ $\left[(1-e^{-b_2})(e^{-a_2}) + \frac{1}{2}(1-e^{-a_2})(1-e^{-b_2})\right]$	$\pi_A = \frac{1-\delta}{2}V$ $\pi_B = \frac{3+\delta}{2}V$	$\pi_A = 0$ $\pi_B = (1+\delta)V$
(B, A)	$[(1-e^{-b_1})(e^{-a_1}) + \frac{1}{2}(1-e^{-b_1})(1-e^{-a_1})] \cdot$ $\left[(1-e^{-a_2})(e^{-b_2}) + \frac{1}{2}(1-e^{-b_2})(1-e^{-a_2})\right]$	$\pi_A = V$ $\pi_B = V$	$\pi_A = V$ $\pi_B = V$
(A, B)	$[(1-e^{-a_1})(e^{-b_1}) + \frac{1}{2}(1-e^{-a_1})(1-e^{-b_1})] \cdot$ $\left[(1-e^{-b_2})(e^{-a_2}) + \frac{1}{2}(1-e^{-a_2})(1-e^{-b_2})\right]$	$\pi_A = V$ $\pi_B = V$	$\pi_A = V$ $\pi_B = V$

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

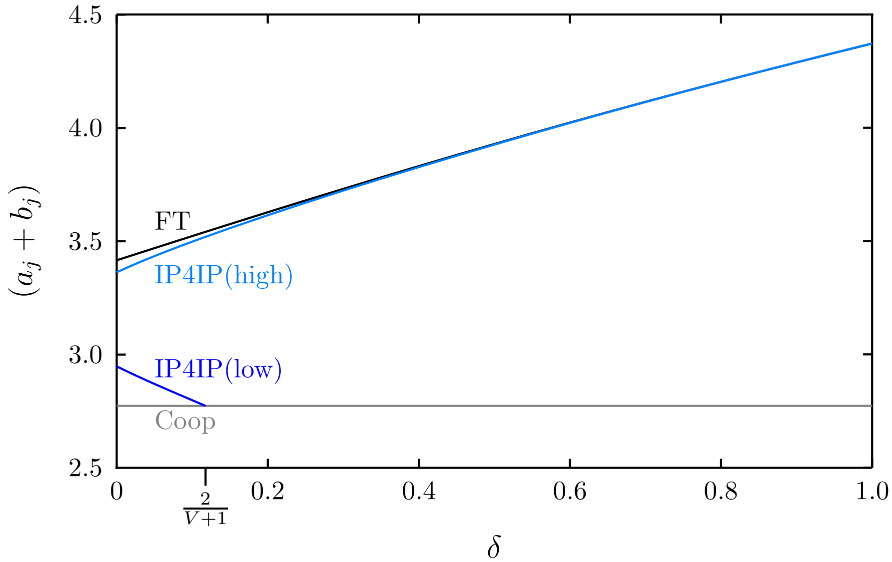

Figure 1: R&D budgets ($V = 16$)

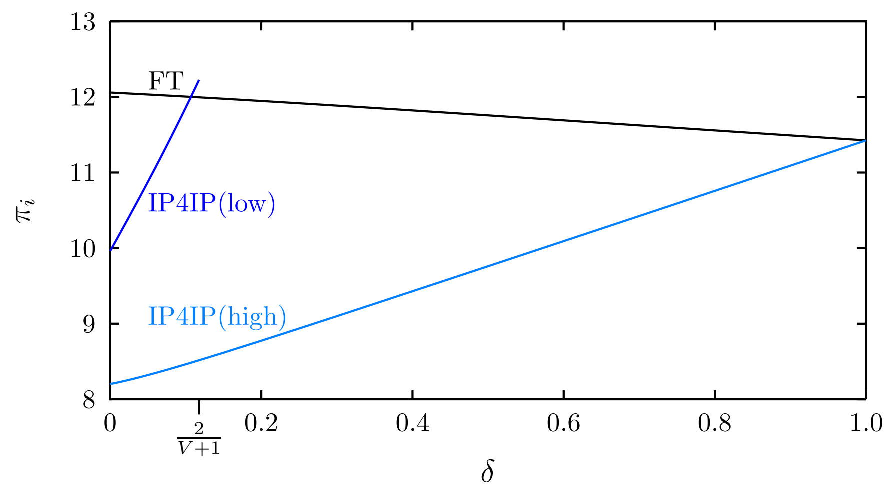

Figure 2: Expected profits ($V = 16$)

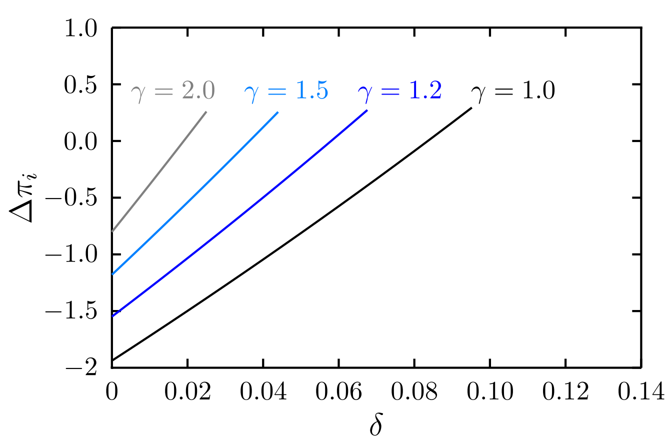

Figure 3: Feature complementarity: Profitability of IP-for-IP strategy ($V = 20$)

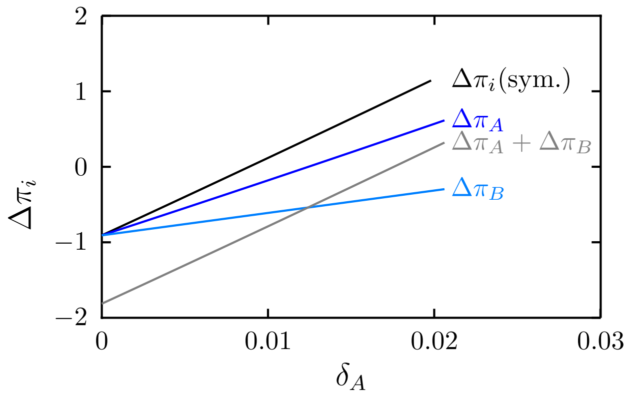

Figure 4: Asymmetric firms: Profitability of IP-for-IP strategy ($V = 100$)