

Intellectual property rights and R&D coordination*

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Abstract

We look at cumulative innovations and the protection of basic research which does not carry stand-alone commercial values in an international setting. Due to the complementarity of the innovations, we find that for some parameter range, technology leading countries do not always prefer the strongest protection standard. On the other hand, technology lagging countries do not always prefer the weakest protection standard. Intellectual property rights may be an instrument to soften R&D competition and may be used to coordinate R&D efforts. Our model suggests that there may be less disputes on intellectual property right standards among countries in industries characterised by sequential innovations.

1 Introduction

We analyze countries' incentives to enforce intellectual property rights by considering a patent race model consisting of a research stage (R) and a development stage (D). To emphasize the problem of complementarity and insufficient appropriation, we assume that the R stage output is necessary for the D stage, but it does not carry any stand-alone commercial value. The strength of IPR protection is measured by the share of profit granted to the inventor who completes the R stage innovation. We assume that there is spill-over of the research output, and firms can engage in D stage research as long as one firm has successfully completed the R stage in the first period.¹ When IPR protection is weak, the first inventor gets a small share of the profit. A strong IPR standard grants the inventor who owns the R stage research output a large share of profit.

*We thank Jota Ishikawa for his comments on a related paper Aoki and Kao (2012). All remaining errors are ours.

¹The channels through which spill-overs can take place are documented in several studies such as Mansfield (1985), Mansfield *et al.* (1981), Levin *et al.* (1987), and Neven and Siotis (1996).

In this paper, we look at the IPR regime in the international setting with two firms and two countries. We study both symmetric and asymmetric cases. For asymmetric country analysis, we study the case that after the R stage, inventors' positions are asymmetric with one technology leader and one technology follower.² The analysis of asymmetric countries complements the literature on the North versus the South debate on intellectual property rights. For symmetric countries, we look at the optimal IPR regime in the beginning of the R stage when the two countries have the same R&D capacity.

We argue that IPR protection may serve as a mechanism for international R&D coordination. With the research output in the R and D stages being complements, stronger IP protection may serve as the device to soften competition in the innovation market. One interesting feature of this model is that with IPR protection, the technology leader gets some share of the follower's profit if the latter completes the patent race. Therefore, the success of the rival does not necessarily harm the firm and depending on the parameter values, an inventor may wish to encourage the rival's R&D investment.

For the asymmetric country case with the focus on the D stage research incentives, our result indicates that it is not necessarily the case that the technology follower always wants the IPR protection level to be as weak as possible. Stronger IPR protection can be used as an instrument to soften the D stage competition. In particular, for industries with high research costs and high probability of success in the D stage, the follower may prefer to grant more IPR protection and encourage the leader not to invest in the D stage. Therefore, for the North-South IPR protection debate, the South may benefit from strengthening IPR protection in innovations where its application is costly to implement but the likelihood of success is high.

On the other hand, setting a very strong IPR protection may not always be advantageous to the leader either. When the likelihood of discovery and the research cost in the D stage are small, the leader may wish to set a weaker IPR protection and encourage the follower to invest in the D stage to increase the likelihood of making a discovery. In these industries, developed countries may benefit from lowering the IPR standard.

When research incentives in both stages are taken into consideration, we show that even with our symmetric setting, for some parameter values, there exists equilibrium where firms specialize in R and D: only one firm invests in the R stage, and conditional on its success, only the other firm invests in the D stage. IP protection can be used to coordinate international R&D effort.

The layout of the paper is as follows. Section two presents a brief review of the related literature. Section three introduces the model set up. We then

²Asymmetry here refers to asymmetric positions, not asymmetric research capacities. A firm is a technology leader if in the end of the R stage race, it has made discovery for R stage research output while the rival has not.

analyze the game starting with the D stage, followed by the analysis of the whole game starting from the beginning of the R stage. Finally, Section 6 concludes. Most proofs are collected in the appendix.

2 Related Literature

Our paper relates to several strands of literature. For the D stage analysis, we focus on the protection levels set by countries with asymmetric R stage research outcomes. This is related to the analysis on trade related aspects of intellectual property rights (TRIPs). A few important issues in this literature include: if there is a coordination problem in setting IPR policies; if the policy can correct the externality generated by innovation; what the incentive compatible policy would be for the South; what the global welfare maximising policy would be; whether or not there is welfare gain by harmonising IPR protection among nations. We only review a few papers which are more closely related to ours. Most papers in this literature employ a multi-sector trade model while we have a strategic patent race framework.

Secondly, the policy instrument that we study in this paper is the share of profit granted to the basic technology. This relates to literature on sequential innovation and research joint venture (RJV). Most of the papers in the literature consider an innovation problem within a country while we analyse the game between two countries.

2.1 North versus South debate

The TRIPs agreements were included in the GATT Uruguay Round negotiation with enforcement and dispute appeal mechanisms and specify the minimum standard for IPR protection for member countries. While most economists agree that liberalisation on trade and services is in general welfare enhancing for all member countries, the welfare effects of TRIPs is more controversial.³ The argument for strengthening IPR in developing countries is to correct for the externality created by the inventors in developed countries. Due to the asymmetry in R&D capacity, it is difficult to argue for a case when the South can generate enough dynamic gain to offset the static loss. This line of argument suggests that TRIPs represent welfare redistribution among countries, with developed countries, the USA in particular, being the main beneficiary.

In a two-country analysis, Deardorff (1992) shows that extending IPR protection raises welfare for the inventing country while the welfare to the other country may fall and it is never optimal to extend the patent protection to the entire world. Helpman (1993) uses a dynamic general equilibrium model and

³See Maskus (2000) for a review of how national differences give rise to different IP policies and how IP policies affect trading relationships and foreign direct investment.

concludes that less developed countries (LCDs) necessarily lose from tighter IPRs while developed countries may gain or lose. When the rate of imitation is slow, a tightening of IPRs hurts both regions. When the rate of imitation is high, developed countries gain while LCDs lose from strengthening IPRs. These papers assume that only the North has the research capacity and do not consider the simultaneous choice of IPR protection levels by trading partners. Glass and Saggi (2002) show that a strengthening of IPR protection in the South would reduce the rate of innovation. Lai (1998) finds that the effects of strengthening IPRs depend on the channels of technology transfer from the North to the South. Most studies at best reach ambiguous welfare conclusion for TRIPs.⁴

Aoki and Prusa (1993) analyze the effects of national treatment and discriminatory IPR protection for foreign inventors. They conclude that discriminatory protection may not increase domestic R&D. They analyse the home market and do not consider the foreign government's reaction. Sato (2001) analyzes a similar situation to what we consider. Two monopolistic firms in two countries, a technological leader and a technological late-comer, engage in R&D to produce similar products and compete in a third market. In the model, only the technology leader can conduct the basic research, and the technology laggard imports the basic technology. Both firms then compete in R&D for the applied technology. Sato constructed the conditions under which the technology laggard without a comparative advantage in the applied technology can win the race. However, in the paper, firms can choose the level of technology spill-over as well as the level of cost sharing in the basic research stage, and the two variables are not correlated. Suzawa (2002) argues that with some dependence between these two variables, the paradox Sato presented would not emerge.

Poyago-Theotoky and Teerasuwannajak (2013) also reach the conclusion that the country with higher research capacity does not always prefer perfect patent protection. Countries in their model differ in terms of research capacities. They do not look at strategic setting of protection levels between the countries and only analyze the polar cases of complete or zero research spillovers. This paper is similar to the settings in Aoki and Kao (2012) where the first stage analysis is largely done by numerical examples. The current paper supplements Aoki and Kao (2012) and present some analytical characterization in the first stage game.⁵

⁴Some papers argue that while developing countries lose in TRIPS agreements, they can be compensated in the accompanying trade liberalisation. Property right protection can be supplemented by trade policies. See for example, discussion in Lai and Qiu (2003, 2004), Grossman and Lai (2003), Žigić (2000), Ishikawa (2007), and Horiuchi and Ishikawa (2009).

⁵In Aoki and Kao (2012), firms move sequentially in the R&D game. Countries also move sequentially in setting the IPR. The current paper features simultaneous games.

2.2 RVJ and multi-stage R&D competition

In our model, the share of profit awarded to the technology owner of the basic research impacts on firms' research incentives. It is similar to mechanisms used for profit sharing in research joint ventures (RJVs). However, in a two country analysis, two countries do not have to agree upon a common share. We review some literature on RJVs and multi-stage R&D competition in this section.

Aghion and Tirole (1994) and Green and Scotchmer (1995) analyze multi-stage patent races with R&D knowledge-selling arrangements and study how the profit should be divided between two inventors. In their setting, each inventor is only capable of doing one stage of research. Therefore, the basic research owner does not face the trade-off of more competition in the D stage. Our model assumes that both inventors can conduct research in both stages.

Denicolo (2002) analyzes the optimal degree of forward patent protection for the first invention. He shows that strong protection is less preferred if the first innovation is more valuable or if the likelihood of making a discovery is high. Intuitively, when the inventor can extract sufficient rent without patent protection, strong forward protection is not necessary. We also show that the optimal share granted to the first invention is larger when the R stage research is costly or the likelihood of success is low. Aoki and Nagaoka (2009) extend Denicolo's model and consider the patentability of the intermediate technology. The alternative to patent is trade secrecy. The patentability of the intermediate technology can be interpreted in the similar fashion as the level of IPR protection in this paper. Denicolo and Aoki and Nagaoka assume constant returns to scale for innovation in their models. Having more firms in the patent race will not increase the return from innovation. Therefore, the inventor always prefers to be the only one pursuing the D stage research if it has completed the R stage. In our framework, having more firms participating in the D stage increases the probability that the discovery will be made. A firm might prefer that the rival does not drop out in the patent race.

Some aspect of our modelling approach is close to Bloch and Markowitz (1996). The focus of their paper is on the optimal disclosure delay, and the optimal policy is the one which minimises the expected discovery time of the innovation. They model a discrete version of Grossman and Shapiro (1987) and assumes fixed cost R&D investment and constant discovery probability. Unlike the conclusion of Bloch and Markowitz and Grossman and Shapiro and many other papers in the patent race literature (for examples Fudenberg *et al.* (1983) and Harris and Vickers (1987)), the technology leader in our model does not always have higher incentive to invest compared with the follower. The level of IPR protection plays an important role for the leader in deciding whether or not to enter the D stage race. All of the above papers consider the case of domestic inventors.

3 Model Setup

The model is a two-stage R&D race game. The first stage represents the research (R) stage and the second stage is the development (D) stage. We assume that the first stage invention carries no stand-alone commercial value and inventors only receive profit after the completion of the D stage.⁶ There are two inventors, A and B , residing in countries A and B respectively, racing each other in this innovation game. Inventors move simultaneously in each stage and we focus on pure strategy Nash equilibrium.

An inventor's R&D progress is indexed by its position in the R&D race, $s_i \in \{0, 1, 2\}$. Position $s_i = 0$ indicates that inventor i is at the starting point of the R&D race, $s_i = 1$ means that inventor i has finished the R stage, and $s_i = 2$ indicates that inventor i has completed the D stage. We analyse the cases for both asymmetric and symmetric inventors. For asymmetric inventors, we analyse the subgame when the R stage competition is concluded and firms' positions are $\{0, 1\}$. For symmetric inventor case, we analyse two different cases: firms' behaviour after the R stage competition when the positions are $\{1, 1\}$ and firms' behaviour from the beginning of the R stage with positions $\{0, 0\}$.⁷

There is complete information in this game. In the beginning of the first stage, standing at position 0, firms decide whether or not to invest in the R stage simultaneously. The investment cost is c_R . If a firm invests, it completes the R stage with probability p_R . Otherwise, it stays at position zero. In the beginning of the second stage, knowing its own and the rival's research outcome in the R stage, firms decide whether or not to invest in the D stage simultaneously. The R&D technology for the D stage is defined in the same fashion with the fixed cost being c_D and the probability of success being p_D . We assume that it is not possible to finish both inventions in one period. There is spill-over once any firm completes the R stage invention. The inventor which failed in the first stage research can engage in the D stage if the rival has the R stage research output.

When an inventor is successful in the R stage research and is the only one to make the D stage discovery, it gets the monopoly profit π_M . When both inventors complete the R stage and both get to position 2 in the end of the second stage, they each gets the duopoly profit π_D . We assume $\pi_M \geq 2\pi_D$. When the R and D stage discoveries are made by different inventors, they share the profit. Let λ , $\lambda \in [0, 1]$, denote the share of profit granted to the R stage technology. For example, if one inventor completes the R stage while the other completes the D stage, the former gets $\lambda\pi_M$ and the latter gets $(1 - \lambda)\pi_M$. If

⁶This assumption simplifies the analysis and emphasises the first inventor's incentive to encourage research in the D stage. The results carry through even if the intermediate technology has some stand-alone value as long as the completion of the D stage adds significant value to the R stage invention.

⁷The situation that firms are asymmetric in terms of different innovative capacity is not modelled.

both firms compete the D stage while only one firm came up with the R stage discovery, the one with the basic research gets $(1 + \lambda) \pi_D$ while the other one gets $(1 - \lambda) \pi_D$. The variable λ thus measures the degree of IPR protection for basic research. $\lambda = 0$ corresponds to the case of free imitation. $\lambda = 1$ corresponds to extreme protection of the basic research output and the inventor which fails in the first period research would drop out from D stage competition. For the two country analysis, we assume national treatment for the foreign inventor and the same degree of protection is offered to both the domestic and foreign firms.⁸ The game finishes after two periods, whether or not inventors have reached the finishing line.

The timing is that in the first stage, two countries set λ simultaneously. In the second stage, firms compete in R stage. In the third and final stage, firms compete in D stage. The game is solved backwards to obtain the subgame perfect Nash equilibrium. Each country takes into consideration both profit in the domestic market and profit in the foreign market. Countries can set different λ s. Strategic interaction between countries matter.

4 D stage equilibrium

We discuss two subgames here: symmetric positions after the R stage game with $(s_A, s_B) = (1, 1)$ and asymmetric positions after the R stage game with $(s_A, s_B) = (0, 1)$. The case $(s_A, s_B) = (0, 0)$ is trivial and the following discussion only focuses on the case where at least one firm has made the R stage discovery after the first period. The case $(s_A, s_B) = (1, 0)$ is symmetric to $(s_A, s_B) = (0, 1)$ with firm's indexes swapped.

For positions $(s_A, s_B) = (1, 1)$, the payoff matrix is given in Table 1.

A \ B	I	NI
I	$2p_D(\pi_M - p_D(\pi_M - \pi_D)) - c_D$, $2p_D(\pi_M - p_D(\pi_M - \pi_D)) - c_D$	$2p_D\pi_M - c_D, 0$
NI	$0, 2p_D\pi_M - c_D$	$0, 0$

Table 1: D stage normal form for the global setting when $(s_A, s_B) = (1, 1)$

If the cost is small, $c_D \leq 2p_D(\pi_M - p_D(\pi_M - \pi_D))$, then investing is a dominant strategy (Cases 1, 2, 3, and 6 in Figure 1). If the cost is very large, $c_D \geq 2p_D\pi_M$, then not investing is dominant (Cases 5 region in Figure 1). For

⁸National treatment is required in TRIPs. This assumption is also employed in Lai and Qiu (2003) and Grossman and Lai (2003).

intermediate levels, only one firm invests (Cases 4 and 7). A firm's best response is to not invest if the other firm invests, and invest if the other firm does not.

For positions $(s_A, s_B) = (0, 1)$, the pay-off matrix is listed below in Table 2.

$A \setminus B$	I	NI
I	$p_D (2 - \lambda_A - \lambda_B) (\pi_M - p_D (\pi_M - \pi_D))$, $-c_D$	$p_D (2 + \lambda_A + \lambda_B) (\pi_M - p_D (\pi_M - \pi_D))$, $-c_D$
NI	$0, 2p_D \pi_M - c_D$	$0, 0$

Table 2: D stage normal form for the global market when $(s_A, s_B) = (0, 1)$

Again, if c_D is small, then investing is the dominant strategy (Case 1). If the cost is large, then not investing is dominant (Case 5). The intermediate range has three parts. If A invests, B invests if $c_D \leq p_D [2\pi_M - (2 + \lambda_A + \lambda_B) p_D (\pi_M - \pi_D)]$. If A does not invest, B invests if $c_D \leq 2p_D \pi_M$. When B invests, A invests if $c_D \leq p_D (2 - \lambda_A - \lambda_B) (\pi_M - p_D (\pi_M - \pi_D))$. When B does not invest, A invests if $c_D \leq p_D (2 - \lambda_A - \lambda_B) \pi_M$. When the positions are $(s_A, s_B) = (1, 0)$, the payoffs are reversed.

Checking the boundary values:

$$p_D [2\pi_M - (2 + \lambda_A + \lambda_B) p_D (\pi_M - \pi_D)] \geq p_D \pi_M (2 - \lambda_A - \lambda_B)$$

if

$$p_D \leq \frac{1}{\left(\frac{2}{(\lambda_A + \lambda_B)} + 1\right)} \left(\frac{\pi_M}{(\pi_M - \pi_D)}\right).$$

And

$$p_D [2\pi_M - (2 + \lambda_A + \lambda_B) p_D (\pi_M - \pi_D)] \geq p_D (2 - \lambda_A - \lambda_B) (\pi_M - p_D (\pi_M - \pi_D))$$

if

$$p_D \leq \frac{\pi_M}{2(\pi_M - \pi_D)}.$$

The D stage equilibrium is depicted in (p_D, c_D) space in Figure 1.

4.1 Optimal protection level in the D stage for asymmetric countries

In this section, we present the optimal protection level for the R stage research output if the countries were to maximise the domestic firm's global profit. Note that each country's chosen policy only affect firms' profit in the given country.

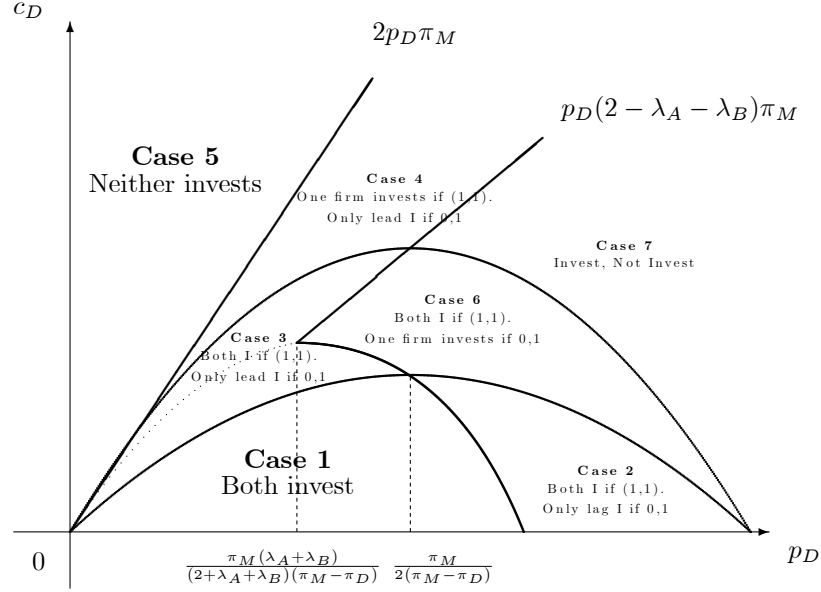


Figure 1: Equilibrium in the D stage when the global market is considered.

Lemma 1 Given positions $(s_A, s_B) = (0, 1)$, for $c_D \leq (2 - \lambda_A - \lambda_B)p_D\pi_M$ and $c_D \leq (2 - \lambda_A - \lambda_B)p_D\pi_M$, A's best response is to set $\lambda_A = \frac{p_D(2\pi_M - p_D(\pi_M - \pi_D)(2 + \lambda_B)) - c_D}{p_D^2(\pi_M - \pi_D)}$. λ_A decreases in λ_B . B's best response is to set $\lambda_B = 1$.

Proof. See the Appendix. ■

Proposition 1 For $c_D \geq \frac{2\pi_M p_D(\pi_M - 2p_D(\pi_M - \pi_D))}{\pi_M - p_D(\pi_M - \pi_D)}$, $\lambda_A = \frac{p_D(2\pi_M - 3p_D(\pi_M - \pi_D)) - c_D}{p_D^2(\pi_M - \pi_D)}$ and $\lambda_B = 1$ is an equilibrium.

Proof. Solve for the intersection point of the best responses given in Lemma 1 and substitute the solution for the c_D condition. ■

Lemma 2 Given positions $(s_A, s_B) = (0, 1)$, for $c_D \leq 2p_D(\pi_M - 2p_D(\pi_M - \pi_D))$, the best responses are $\lambda_A = 0$ and $\lambda_B = 2 - \lambda_A - \frac{c_D}{p_D(\pi_M - p_D(\pi_M - \pi_D))}$.

Proof. See the Appendix. ■

Proposition 2 Given positions $(s_A, s_B) = (0, 1)$, for $c_D \geq p_D(\pi_M - p_D(\pi_M - \pi_D))$ and $c_D \leq 2p_D(\pi_M - 2p_D(\pi_M - \pi_D))$, $\lambda_A = 0$ and $\lambda_B = 2 - \frac{c_D}{p_D(\pi_M - p_D(\pi_M - \pi_D))}$ is an equilibrium.

Proof. Solve for the intersection point and parameter range given in Lemma 2 and add the condition to ensure that $\lambda_B \in [0, 1]$. ■

5 R stage equilibrium

We present the payoff matrix at the start of the R stage in Table 3.

A\B	I	NI
I	$p_R(p_R\pi_{11} + (1 - p_R)\pi_{10}) + (1 - p_R)p_R\pi_{01} - c_R$	$p_R(p_R\pi_{11} + (1 - p_R)\pi_{01}) + (1 - p_R)p_R\pi_{10} - c_R$
NI	$p_R\pi_{01}, p_R\pi_{01} - c_R$	$p_R\pi_{10}, p_R\pi_{10} - c_R$
		$0, 0$

Table 3: R stage normal form for the global market setting..

The *ex ante* expected payoff in the R stage would depend on the D stage equilibrium. We present the expected payoff according to the D stage equilibrium listed in Figure 1.

The firms' *ex ante* expected payoffs are symmetric. When only one firm invests in the equilibrium, for the ease of exposition, I present the payoff below for *A* invests.

Case 1

$$\begin{aligned}\pi_A [\mathbf{I}, \mathbf{I}] &= \pi_B [\mathbf{I}, \mathbf{I}] \\ &= 2p_R p_D (2 - p_R) (\pi_M - p_D (\pi_M - \pi_D)) - p_R c_D (2 - p_R) - c_R;\end{aligned}$$

$$\begin{aligned}\pi_A [\mathbf{I}, \mathbf{NI}] &= \pi_B [\mathbf{NI}, \mathbf{I}] \\ &= p_R (p_D (2 + \lambda_A + \lambda_B) (\pi_M - p_D (\pi_M - \pi_D)) - c_D) - c_R;\end{aligned}$$

$$\begin{aligned}\pi_A [\mathbf{NI}, \mathbf{I}] &= \pi_B [\mathbf{I}, \mathbf{NI}] \\ &= p_R \pi_{01} = p_R (p_D (2 - \lambda_A - \lambda_B) (\pi_M - p_D (\pi_M - \pi_D)) - c_D);\end{aligned}$$

Case 2 Inventors' payoffs are symmetric in this case.

$$\begin{aligned}\pi_A [\mathbf{I}, \mathbf{I}] &= \pi_B [\mathbf{I}, \mathbf{I}] \\ &= 2p_R p_D (\pi_M - p_R p_D (\pi_M - \pi_D)) - p_R c_D - c_R;\end{aligned}$$

$$\begin{aligned}\pi_A [\mathbf{I}, \mathbf{NI}] &= \pi_B [\mathbf{NI}, \mathbf{I}] \\ &= p_R \pi_{10} - c_R = (\lambda_A + \lambda_B) p_R p_D \pi_M - c_R;\end{aligned}$$

$$\begin{aligned}\pi_A [\mathbf{NI}, \mathbf{I}] &= \pi_B [\mathbf{I}, \mathbf{NI}] \\ &= p_R \pi_{01} = p_R [p_D (2 - \lambda_A - \lambda_B) \pi_M - c_D];\end{aligned}$$

Case 3

$$\begin{aligned}\pi_A [\text{I}, \text{I}] &= \pi_B [\text{I}, \text{I}] \\ &= 2p_R p_D (\pi_M - p_R p_D (\pi_M - \pi_D)) - p_R c_D - c_R;\end{aligned}$$

$$\begin{aligned}\pi_A [\text{I}, \text{NI}] &= \pi_B [\text{NI}, \text{I}] \\ &= p_R (2p_D \pi_M - c_D) - c_R;\end{aligned}$$

$$\pi_A [\text{NI}, \text{I}] = \pi_B [\text{I}, \text{NI}] = \pi_A [\text{NI}, \text{NI}] = \pi_B [\text{NI}, \text{NI}] = 0.$$

Case 4 For the firm which invests when positions are (1, 1) in the D stage:

$$\pi_A [\text{I}, \text{I}] = p_R (2p_D \pi_M - c_D) - c_R;$$

$$\pi_A [\text{I}, \text{NI}] = p_R (2p_D \pi_M - c_D) - c_R;$$

$$\pi_A [\text{NI}, \text{I}] = 0.$$

For the firm which does not invests when positions are (1, 1) in the D stage:

$$\pi_B [\text{I}, \text{I}] = p_R (1 - p_R) (2p_D \pi_M - c_D) - c_R;$$

$$\pi_B [\text{I}, \text{NI}] = 0;$$

$$\pi_B [\text{NI}, \text{I}] = p_R (2p_D \pi_M - c_D) - c_R;$$

Case 5 In this case, the research cost in the D stage is prohibitively high such that no inventors carry out research in the D stage. The equilibrium in the R stage is (NI, NI).

Case 6 For the firm which invests when positions are $\{0, 1\}$ in the D stage:

$$\begin{aligned}\pi_A [\text{I}, \text{I}] &= p_R p_D (4\pi_M - 2p_R \pi_M - 2p_R p_D (\pi_M - \pi_D)) - (1 - p_R) (\lambda_A + \lambda_B) \pi_M \\ &\quad - 2p_R c_D + p_R^2 c_D - c_R;\end{aligned}$$

$$\pi_A [\text{I}, \text{NI}] = p_R \pi_{10} - c_R = p_R (2p_D \pi_M - c_D) - c_R;$$

$$\pi_A [\text{NI}, \text{I}] = p_R \pi_{01} = p_R (p_D (2 - \lambda_A - \lambda_B) \pi_M - c_D);$$

For the firm which does not invest when positions are $\{0, 1\}$ in the D stage:

$$\begin{aligned}\pi_B [\text{I}, \text{I}] &= p_R^2 (2p_D (\pi_M - p_D (\pi_M - \pi_D)) - c_D) \\ &\quad + (1 - p_R) p_R ((\lambda_A + \lambda_B) p_D \pi_M) - c_R;\end{aligned}$$

$$\pi_B [\text{I}, \text{NI}] = 0;$$

$$\pi_B [\text{NI}, \text{I}] = p_R ((\lambda_A + \lambda_B) p_D \pi_M) - c_R;$$

Case 7 For the firm which invests in the D stage:

$$\pi_A [I, I] = \pi_M p_R p_D (4 - 2p_R - (\lambda_A + \lambda_B)(1 - p_R)) - p_R c_D (2 - p_R) - c_R;$$

$$\pi_A [I, NI] = p_R (2p_D \pi_M - c_D) - c_R;$$

$$\pi_A [NI, I] = p_R (p_D (2 - \lambda_A - \lambda_B) \pi_M - c_D);$$

For the firm which invests in the D stage:

$$\pi_B [I, I] = (\lambda_A + \lambda_B)(1 - p_R) p_R p_D \pi_M - c_R;$$

$$\pi_B [I, NI] = \pi_B [NI, NI] = 0;$$

$$\pi_B [NI, I] = (\lambda_A + \lambda_B) p_R p_D \pi_M - c_R;$$

Proposition 3 *There exists some parameter range such that in equilibrium, one country invests in the R stage while the other country invest in the D stage.*

Proof. We construct the parameter range such that the D stage equilibrium can occur in Case 2 where only the lagging firm invests in the D stage if the positions are asymmetric. We then work out the condition for the condition for the R stage equilibrium to be such that only one firm invests. The equilibrium of the whole game is that one firm invests in the R stage and the other firm invests in the D stage. See the appendix for details. ■

To illustrate such an equilibrium where firms specialize in one stage of innovation, we present the following example:

Example 1 *Parameter values: $\pi_M = 3$, $\pi_D = 1$, $p_D = 0.8$, $c_D = 0.8$, $c_R = 0.8$, $p_R = 0.8$, $\lambda_A = 0.4$, $\lambda_B = 0.87$. With the given parameter values, the resulting D stage payoff matrix is:*

For positions (1, 1):

A \ B	I	NI
I	1.44, 1.44	4, 0
NI	0, 4	0, 0

For positons (0, 1):

A \ B	I	NI
I	0.0176, 2.8624	0.952, 3.048
NI	0, 4	0, 0

The D stage equilibrium is in Case 2 where both firms invest if the positions are even and only the lagging firm invests if the positions are asymmetric.

In the beginning of the R stage, given the D stage equilibrium, we have the payoff matrix:

A \ B	I	NI
I	0.7616, 0.7616	1.6384, 0.7616
NI	0.7616, 1.6384	0, 0

(I, NI) and (NI, I) are both Nash equilibria. These two Nash equilibria Pareto dominates the other equilibrium (I, I).

6 Conclusions

We have analysed inventors' investment incentives when the patent race consists of two complementary stages. When we only focus on the D stage competition and take inventors' initial positions as given, our result indicates that when p_D and c_D are large, the follower may prefer setting a higher λ and encourage the leader not to invest in the D stage. Therefore, for the North-South IPR protection debate, if the development of a new product requires a research stage and a development stage, the South may benefit by strengthening IPR protection in innovations where its application is costly to implement but the likelihood of success is high. On the other hand, when p_D and c_D are small, the leader may wish to set a lower λ and encourage the follower to invest in the D stage to increase the chance of making a discovery. In these industries, developed countries may benefit by lowering the IPR protection.

When research incentives in both stages are taken into account, we show that for some parameter ranges, even symmetric countries choose asymmetric levels of IPR protection in equilibrium. Furthermore, harmonisation of IPR protection across countries may not be welfare enhancing. In general, the optimal λ decreases in p_R and c_D and increases in c_R and p_D . In the global setting where countries can choose different λ s, the first mover's optimal λ decreases in that of the second mover's.

We have assumed sequential move for the two-stage R&D game. The result indicates that the sequence of move is important and there is a first mover advantage. It would be beneficial for countries to try to invest in the patent race early. For most parameter ranges, the first mover sets a lower λ compared with the second mover. For some parameter ranges, it is optimal to select a λ and make each inventor specialise in one stage of research.

Our analysis can be extended in many ways. The first one is that for an international setting, trade in goods can work as a complement or substitute for trade in knowledge. The inclusion of tradeable goods would make the analysis more comprehensive and would also make it comparable the international trade literature.

Secondly, for the two country analysis when research incentives are included, we assume that countries have the same innovative capacity. That is, firms share the same technology parameters. It could be extended to consider asymmetric countries with different p_R and p_D . We can analyse the equilibrium when one country has absolute advantage in carrying out research in both stages and the case that neither of them enjoys absolute advantage. Our conjecture is that if countries are asymmetric, there should be more gains from trade in technology and it would emphasise the need for international research cooperation. It may be more likely that countries would specialise in R and D.

Finally, in the model, it is assumed that it is not possible to catch up and

come up with the R stage technology in the second period. If the catching up behaviour is possible, the parameter for this leapfrogging probability would affect the equilibrium in this two stage R&D race.

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7 Appendix

7.1 Proofs of results

Proof. of Lemma 1: $\pi_A((I, NI) | s_A = 0, s_B = 1) > \pi_A((I, I) | s_A = 0, s_B = 1)$. When A invests, it always prefers that B does not invest. To make B not to

invest, we need $\pi_B((I, NI) | s_A = 0, s_B = 1) > \pi_B((I, I) | s_A = 0, s_B = 1)$. Or

$$\lambda_A \geq \frac{p_D(2\pi_M - p_D(\pi_M - \pi_D)(2 + \lambda_B)) - c_D}{p_D^2(\pi_M - \pi_D)}.$$

Note that

$$\frac{p_D(2\pi_M - p_D(\pi_M - \pi_D)(2 + \lambda_B)) - c_D}{p_D^2(\pi_M - \pi_D)} \leq 1.$$

if $c_D \geq p_D(2\pi_M - p_D(2 + \lambda_B)(\pi_M - \pi_D))$. $\pi_A((I, NI) | s_A = 0, s_B = 1) > \pi_A((NI, NI) | s_A = 0, s_B = 1)$ and A invests when B does not invest if $c_D \leq (2 - \lambda_A - \lambda_B)p_D\pi_M$. When the two conditions are satisfied simultaneously, the equilibrium is that A invests with the best response $\lambda_A = \frac{p_D(2\pi_M - p_D(\pi_M - \pi_D)(2 + \lambda_B)) - c_D}{p_D^2(\pi_M - \pi_D)}$. B 's best response is $\lambda_B = 1$. ■

Proof. of Lemma 2: When B does not invest, it always prefers that A invests. When B invests, it prefers that A invests if $\lambda_B \geq \frac{2\pi_M}{(\pi_M - p_D(\pi_M - \pi_D))} - (2 + \lambda_A)$. This is the minimum λ required for B 's incentive constraint.

When B invests, A prefers investing if $2 - \lambda_A - \frac{c_D}{p_D(\pi_M - p_D(\pi_M - \pi_D))} \geq \lambda_B$. This is the upper bound for λ_B given that A 's incentive constraint must be satisfied.

$$2 - \lambda_A - \frac{c_D}{p_D(\pi_M - p_D(\pi_M - \pi_D))} \geq \frac{2\pi_M}{(\pi_M - p_D(\pi_M - \pi_D))} - (2 + \lambda_A)$$

if $c_D \leq 2p_D(\pi_M - 2p_D(\pi_M - \pi_D))$. B prefers investing when A invests if

$$c_D \leq p_D(2\pi_M - p_D(2 + \lambda_A + \lambda_B)(\pi_M - \pi_D)).$$

This is always satisfied if $c_D \leq 2p_D(\pi_M - 2p_D(\pi_M - \pi_D))$. Therefore, for $c_D \leq p_D(2\pi_M - 4p_D(\pi_M - \pi_D))$, B 's best response is $\lambda_B = 2 - \lambda_A - \frac{c_D}{p_D(\pi_M - p_D(\pi_M - \pi_D))}$.

For A , when both firms invest, π_A decreases in λ_A and it always prefers setting $\lambda_A = 0$. ■

Proof. of Proposition 3. For the D stage game equilibrium to be in Case 2, we need ■

$$p_D(2\pi_M - (2 + \lambda_A + \lambda_B)p_D(\pi_M - \pi_D)) \leq c_D \leq p_D(2 - \lambda_A - \lambda_B)(\pi_M - p_D(\pi_M - \pi_D)) \quad (\text{A1})$$

and

$$p_D \geq \frac{\pi_M}{2(\pi_M - \pi_D)}. \quad (\text{A2})$$

We want to construct the equilibrium such that firm A not invest while firm B invests in the R stage.

In the R stage, if A does not invest, firm B invests if

$$c_R \leq p_R\pi_{01}.$$

Or

$$c_R \leq (\lambda_A + \lambda_B)p_R p_D \pi_M \quad (\text{A3})$$

Given that firm B invests, firm A choose not to invest if

$$p_R [p_D (2 - \lambda_A - \lambda_B) \pi_M - c_D] \geq 2p_{RPD} (\pi_M - p_{RPD} (\pi_M - \pi_D)) - p_{RC} - c_R$$

Or if

$$c_R \geq 2p_{RPD} (\pi_M - p_{RPD} (\pi_M - \pi_D)) - p_{RC} - p_R [p_D (2 - \lambda_A - \lambda_B) \pi_M - c_D]$$

$$c_R \geq p_{RPD} ((\lambda_A + \lambda_B) \pi_M - 2p_{RPD} (\pi_M - \pi_D)) \quad (\text{A4})$$

In the λ setting stage, B chooses λ_B to maximise expected profit. Looking at B 's own profit, B always wants to choose an as high as possible λ_B . But B also wants to set a λ_B such that A does not invest. Thus, the setting of λ_B is constrained by

(A4 and A5 together implies that A is indifferent, thus the result of the R stage payoff)

$$\lambda_B \leq \frac{c_R}{p_{RPD}\pi_M} + 2p_{RPD} \frac{(\pi_M - \pi_D)}{\pi_M} - \lambda_A.$$

The optimal is a corner solution,

$$\lambda_B = \frac{c_R}{p_{RPD}\pi_M} + 2p_{RPD} \frac{(\pi_M - \pi_D)}{\pi_M} - \lambda_A. \quad (\text{A5})$$

For A , A does not invest in the R stage but invests in the D stage, and thus wishes to maximise:

$$p_R [p_D (2 - \lambda_A - \lambda_B) \pi_M - c_D]$$

Taking into consideration of B 's best response,

$$p_R \left[p_D \left(2 - \lambda_A - \left(\frac{c_R}{p_{RPD}\pi_M} + 2p_{RPD} \frac{(\pi_M - \pi_D)}{\pi_M} - \lambda_A \right) \right) \pi_M - c_D \right]$$

The payoff does not depend on λ_A since the effect is completely offsetted by country B . In this model, an increase in λ_A does as well as an increase in λ_B in terms of stimulating innovation. This is very different from the Cournot model for example. An increase of output has a price effect which is shared by all firms. But there is an output effect which is specific to the firm. Given B 's best response and given the second stage game, A 's payoff remains the same as long as there is no regime change.

Now, we should check for the profitability of deviation.

$$\pi_B [I, I] = 2p_{RPD} (\pi_M - p_{RPD} (\pi_M - \pi_D)) - p_{RC} - c_R$$

$$2p_{RPD} (\pi_M - p_{RPD} (\pi_M - \pi_D)) - p_{RC} - c_R \leq (\lambda_A + \lambda_B) p_{RPD} \pi_M - c_R$$

Substitute in the constrained λ_B , the inequality holds if

$$\begin{aligned} & 2p_{RPD} (\pi_M - p_{RPD} (\pi_M - \pi_D)) - p_{RC} - c_R \\ & \leq \left(\lambda_A + \left(\frac{c_R}{p_{RPD}\pi_M} + 2p_{RPD} \frac{(\pi_M - \pi_D)}{\pi_M} - \lambda_A \right) \right) p_{RPD} \pi_M - c_R \end{aligned}$$

$$\begin{aligned}
2p_R p_D (\pi_M - p_R p_D (\pi_M - \pi_D)) - p_R c_D &\leq c_R + 2p_R p_D \frac{(\pi_M - \pi_D)}{\pi_M} p_R p_D \pi_M \\
-4p_R^2 p_D^2 (\pi_M - \pi_D) + 2p_R p_D \pi_M - (c_R + p_R c_D) &\leq 0 \\
4p_R^2 (\pi_M - \pi_D) p_D^2 - 2p_R \pi_M p_D + (c_R + p_R c_D) &\geq 0
\end{aligned}$$

This holds if

$$\frac{\pi_M^2}{4(\pi_M - \pi_D)} \leq (c_R + p_R c_D) \quad (\text{A6})$$

Otherwise, it holds for

$$p_D \leq \frac{\pi_M - \sqrt{\pi_M^2 - 4(\pi_M - \pi_D)(c_R + p_R c_D)}}{4p_R(\pi_M - \pi_D)} \text{ or } p_D \geq \frac{\pi_M - \sqrt{\pi_M^2 - 4(\pi_M - \pi_D)(c_R + p_R c_D)}}{4p_R(\pi_M - \pi_D)} \quad (\text{A7})$$

On the other hand, we now consider possible deviation from firm A .

For firm A , if it deviates to invest in the R stage, if firm B also invests in the R stage, the expected payoff for firm A is

$$\begin{aligned}
\pi_A [I, I] &= \pi_B [I, I] \\
&= 2p_R p_D (2 - p_R) (\pi_M - p_D (\pi_M - \pi_D)) - p_R c_D (2 - p_R) - c_R;
\end{aligned}$$

The expected payoff from NI is

$$p_R \left[p_D \left(2 - \frac{c_R}{p_R p_D \pi_M} - 2p_R p_D \frac{(\pi_M - \pi_D)}{\pi_M} \right) \pi_M - c_D \right].$$

NI is an equilibrium if

$$c_D \geq 2p_D (\pi_M - 2p_D (\pi_M - \pi_D)) \quad (\text{A8})$$

$$p_D (2\pi_M - (2 + \lambda_A + \lambda_B) p_D (\pi_M - \pi_D)) \leq c_D \leq p_D (2 - \lambda_A - \lambda_B) (\pi_M - p_D (\pi_M - \pi_D))$$

$$2p_D (\pi_M - 2p_D (\pi_M - \pi_D)) \leq p_D (2 - \lambda_A - \lambda_B) (\pi_M - p_D (\pi_M - \pi_D))$$

if

$$(\lambda_A + \lambda_B) \leq \frac{2p_D (\pi_M - \pi_D)}{(\pi_M - p_D (\pi_M - \pi_D))} \quad (\text{A9})$$