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Abstract

This paper analyzes the effects of intellectual property rights (IPR) protection on innovation and technology transfer in a North-South quality-ladder model with innovative Northern R&D and adaptive Southern R&D. The degree of IPR protection in two countries differs in terms of patent breadth, which determines the markups of Northern firms and their Southern affiliates, respectively. In this model, stronger IPR protection in the South leads to a permanent decrease in the North-South wage gap, a temporary increase in the Northern innovation rate, and a permanent increase in technology transfer. By contrast, stronger IPR protection in the North leads to a permanent increase in the North-South wage gap, ambiguous effects on the Northern innovation rate, and a permanent decrease in technology transfer. Finally, we perform a quantitative analysis by calibrating the model to the US-China data, and the numerical results support these policy implications.

JEL classification: F12; F23; F43; O31; O34.
Keywords: Intellectual property rights protection; International technology transfer; North-South trade; Multinational firms; Schumpeterian economic growth.

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1 Introduction

The relationship between intellectual property rights (IPR) protection in developing countries (i.e., the South) and the incentives of developed countries (i.e., the North) to transfer technologies has been a fundamental question in the literature on multinational firms and international trade. This relationship has become even more important since the Trade-Related Intellectual Property Rights (TRIPS) Agreement of the World Trade Organization (WTO), which was signed by the WTO members in 1994 to raise the level of IPR protection around the world, especially in developing countries.[1] As a result of international technology transfer, some existing studies argue that strengthening IPR protection in developing countries harms themselves by simply causing income transfer from developing countries to developed countries (e.g., McCalman (2001) and Park and Lippoldt (2005)), but some argue that it could benefit the global economy (e.g., Gustafsson and Segerstrom (2011) and Tanaka and Iwaisako (2014)). Therefore, in order to justify the (dis)advantages of stronger IPR protection in developing countries, this study attempts to reexamine the effects on technology transfer within multinational firms in terms of foreign direct investment (FDI) and on the welfare of both developing and developed countries.[2]

In addition, most existing studies in multinational firms and technology transfer mainly focus on the role of stronger IPR protection in the South.[3] Nevertheless, using the patent rights protection index constructed by Ginarte and Park (1997) and Park (2008), Dinopoulos and Kottaridi (2008) report that during the period 1960-2000, the degree of IPR protection increased significantly not only in developing countries (on average by 70%) but also in developed countries (on average by 50%).[4] In the North-South model setting, stronger IPR protection in the North changes the degree of protection of their intellectual assets, as reflected by the value of patents for innovations. This tends to alter the incentives of Northern firms to conduct research and development (R&D) to develop new innovations and thus generates an reallocation effect on the resources between production and R&D in the North. This resource reallocation in turn affects the amounts of production shifted from the North to the South and the rate of technology transfer accompanied with it. Accordingly, to fully consider the decision of Northern parent firms on innovation and the decision on technology transfer to their Southern affiliates in a more realistic environment, the (long-run) effect of stronger IPR protection in the North should also be taken

[1] In the current literature, the theoretical and empirical conclusions about the impacts of Southern IPR protection on international technology transfer are mixed. For example, the North-South models by Glass and Saggi (2002) and Glass and Wu (2007) show that stronger IPR protection in the South unambiguously reduces the rate of technology transfer, and the empirical analysis of Mayer and Pfister (2001) and Pfister and Deffains (2005) finds a negative effect of stronger patent rights on location decisions of French multinationals. However, the implication of North-South models by Helpman (1993), Lai (1998), and Branstetter and Saggi (2011) is consistent with the observation in Lee and Mansfield (1996), Nunnenkamp and Spatz (2004), and Branstetter *et al.* (2006), such that the increase in foreign direct investment by US multinationals results from stronger IPR protection in developing countries. See Park (2012) for a detailed survey.

[2] The types of technology transfer from developed countries to developing countries can be various, such as FDI, licensing, and illegal imitation. In particular, inward FDI is one of the main modes that becomes increasingly important in developing economies. FDI data from UNCTAD World Investment Report indicate that FDI inflows and inward FDI stock in developing economies grew at an annual rate of about 11.60% and 11.81%, respectively, from 1990 to 2017.

[3] See, for example, Dinopoulos and Segerstrom (2010) and Iwaisako *et al.* (2011).

[4] For example, Park (2008) show that from 1960 to 2000, the Ginarte-Park index increase from 3.86 to 4.88 in the US, from 2.85 to 4.67 in Japan, from 3.20 to 4.54 in the UK, and from 2.33 to 4.50 in Germany.

into consideration.

To properly address the above issues, this study develops a North-South quality-ladder model with semi-endogenous growth that features innovative R&D in the North and adaptive R&D in the South to theoretically and quantitatively analyze the cross-country effects of IPR protection on innovation and international technology transfer.[5] Specifically, in this model, Northern firms engage in innovative R&D to develop new higher-quality products, and to increase profit flows, they (in the form of multinational firms) invest in adaptive R&D to transfer their manufacturing of these products from the high-wage North to the low-wage South. Moreover, to model IPR protection, the analysis in this study focuses on the use of the policy instrument: *patent breadth*, in the North and in the South, respectively. The level of patent breadth captures the degree of protection for the state-of-art technology holders against potential imitations, which determines the monopolistic markups charged by multinational firms and the amount of profits generated by the technology in the two regions. Within this open-economy dynamic general equilibrium framework, we derive the following results.

Stronger patent protection in the South leads to a permanent decrease in the North-South wage gap, a permanent increase in the rate of technology transfer, and a temporary increase in the rate of Northern innovation. Intuitively, a larger patent breadth in the South raises the cost of imitation, which generates more market power to Southern firms by allowing them to charge a higher markup. Hence, the incentives for relocating manufacturing operations to Southern firms through adaptive R&D increase, yielding a higher demand for R&D labor in the South. Consequently, the wage rate in the South rises relative to the North. Furthermore, given that stronger Southern patent protection increases the incentives for being a Southern firm, more adaptive R&D will be performed, yielding a positive effect on the rate of international technology transfer. As a result, a smaller number of products will be manufactured in the North. Therefore, there is a labor reallocation from production to R&D in the North, which in turn increases the rate of Northern innovation but only temporarily since the model has the semi-endogenous-growth property.

Stronger patent protection in the North leads to a permanent increase in the North-South wage gap, a permanent decrease in the rate of international technology transfer, and an ambiguous effect on the rate of innovation in the North depending on the relative size of the two economies.[6] Intuitively, a larger patent breadth in the North increases the profit margin of Northern firms through a larger markup, which decreases the incentives for adaptive R&D. Hence, a lower demand for Southern R&D labor depresses the wage rate in the South relative to the North. Furthermore, given that a larger Northern patent breadth has a negative impact on adaptive R&D, the benefits of remaining as Northern firms increase, which in turn reduces the rate of international technology transfer. Finally, as for the impact on the rate of Northern innovation, there are two contrasting effects: a larger Northern patent breadth raises the demand for Northern R&D labor through a larger markup of Northern firms (i.e., the positive effect) but reduces it through more products being manufactured in the North (i.e., the negative effect). The latter

[5]In Appendix B, we consider an extension in which the model with an alternative R&D specification features fully endogenous growth in the long run. It is shown that the main results of the baseline model would be robust in this extended model.

[6]Specifically, we find that strengthening Northern patent protection would cause a temporary increase (decrease) in the rate of Northern innovation if the Southern population size is smaller (greater) than another threshold value (i.e., $\bar{\alpha}$).

negative effect on the rate of Northern innovation via R&D labor in the North becomes weaker if the Southern labor force is smaller. Therefore, there exists a threshold on the Southern population size below (above) which the overall effect of stronger patent protection in the North on the innovation rate would be positive (negative).

We calibrate our model to the China-US data to quantify the cross-country effects of IPR protection in terms of patent breadth. Our numerical analysis shows that increasing the level of patent breadth in China by 1% (percent change) reduces the wage gap between the US and China by 0.900% (percent change), and it raises the average quality per US worker by 0.577% (percent change), implying a temporary higher rate of innovation in the US. The larger patent breadth in China would increase the flow of technology transfer from the US to China by 5.225% (percent change). Broadening patent breadth in China causes an increase in consumption of 2.141% in China and 1.546% in the US. These welfare gains are mostly due to the increase in wages in both countries.

Additionally, increasing the level of patent breadth in the US by 1% raises the wage gap between the US and China by 0.617% and decreases the flow of technology transfer from the US to China by 3.993%. The larger patent breadth in the US would raise the average quality per US worker by 3.218%, implying a temporary higher rate of innovation in the US, since the size of China's population is smaller than the threshold value in this case. Broadening patent breadth in the US causes an increase in consumption of 9.431% in China and 8.792% in the US. Therefore, broadening patent breadth in the US leads to a significantly larger welfare improvement for the two economies in total than broadening patent breadth in China. Moreover, China tends to benefit more than the US under a strengthening of patent protection in either country. These results highlight the importance of strengthening IPR protection in both developing and developed countries in raising the global economy's welfare, which, to some extent, justifies the objective of TRIPS.

1.1 Literature review

This paper contributes to the theoretical literature on innovation and technology transfer that models IPR protection in forms other than patent breadth. Yang and Maskus (2001) model stronger IPR protection in terms of technology licensing and explore the impacts of reducing licensing costs and improvements in the licensor's share of rents.[7] Dinopoulos and Kottaridi (2008) analyze the effects of IPR policy on innovation and technology transfer by modeling stronger IPR protection as an increase in patent length and/or a strengthening of patent enforcement. Gancia and Bonfiglioli (2008) study how North-South trade affects the direction of technical progress, growth and wage differences, and they model stronger IPR protection by an exogenous fraction of profits earned by successful Southern imitations that accrues to the original innovator. Nevertheless, the analysis of IPR protection in the present paper differs from the above papers by focusing on the scope of products that grants to patented firms to produce, which is captured by the level of patent breadth.[8] Specifically, in the current quality-ladder model, patent breadth represents the degree of quality by which the government in a region permits the state-of-art technology

[7]Tanaka *et al.* (2007) reexamine the policy analysis of the Yang and Maskus (2001) model by studying the steady state and transitional dynamics, respectively.

[8]See Chapter 2 in Maskus (2000) for details about the requirement on WTO member countries to strengthen patent protection in regard to patent breadth by the TRIPS agreement.

holders to produce without potential imitations from competitive fringes, which determines the markups and profits of the monopolistic firms in the North and the South, respectively. In other words, the different levels of Northern patent breadth and Southern patent breadth captures the difference in the market power of the two economies.

This study is closely related to the recent research of Dinopoulos and Segerstrom (2010) and Iwaisako *et al.* (2011), who analyze the effects of IPR protection in North-South quality-ladder models,[9] but there are significant differences between these studies and ours. First, in a model with innovative R&D in the North and adaptive R&D in the South (i.e., costly FDI), Dinopoulos and Segerstrom (2010) investigate the effects of stronger IPR protection in developing countries on innovation, technology transfer, and welfare,[10] and the form of IPR protection is represented by the exogenous instantaneous probability that Southern affiliates' products are copied.[11] By contrast, our study explores the same effects by employing a different IPR policy lever (i.e., broadening patent breadth that enlarges Southern firms' markup). Moreover, Dinopoulos and Segerstrom (2010) show that the long-run welfare effect of stronger IPR protection in the South on domestic consumers is theoretically ambiguous. Despite of the same analytical result in the current study, our paper complements Dinopoulos and Segerstrom (2010) by adding a quantitative analysis to illustrate that such a welfare effect is indeed substantially positive. Second, Iwaisako *et al.* (2011) explore how strengthening IPR protection in the South by increasing patent breadth affects innovation, FDI, and welfare. Nevertheless, similar to the assumption used in Helpman (1993), Lai (1998), and Branstetter and Saggi (2011), the setting of Iwaisako *et al.* (2011) assumes that international technology transfer within multinational firms is costless, which is inconsistent with the recent evidence that the R&D spending by affiliates of US multinationals increased considerably.[12] Our study differs from the analysis of Iwaisako *et al.* (2011) by considering adaptive R&D in Southern affiliates as the approach to transfer the intellectual property that facilitates production from the North to the South. Third, this study takes into account the effects of tightening IPR protection in the North, which conforms to the changes in patent rights of developed countries in the last few decades. Nonetheless, the impact of Northern IPR protection is neglected in the above studies. Therefore, to the best of our knowledge, this is the first study that analyzes the cross-country effects of patent breadth in a Schumpeterian growth model with North-South technology transfer and costly FDI.

The present paper is also related to the existing studies of global patent protection. Lai and Qiu (2003) and Grossman and Lai (2004) analyze the welfare incentives of the Northern and Southern governments to protect their intellectual property rights by using patent length as the policy instrument in an open-economy variety-expanding model where both regions invest in R&D, whereas the current paper differs from their interesting studies by focusing on the important role of national patent policies in the form of patent breadth in an open-economy

[9] See Gustafsson and Segerstrom (2010, 2011) and Lorenczik and Newiak (2012), who explore the effects of IPR protection in a North-South trade model with increasing product variety.

[10] See Ohki (2017) for a similar analysis in a framework where both Northern and Southern firms incur technology transfer costs.

[11] Glass and Saggi (2002) and Glass and Wu (2007) study the effects of stronger IPR protection on innovation and technology transfer, with and without costly FDI, respectively, and the mode of IPR protection in their models is similar to that in Dinopoulos and Segerstrom (2010).

[12] According to The National Science Foundation, the series in International Investment and R&D Data Link reports that the R&D expenditure of the majority-owned foreign affiliate (MOFA) of US multinational companies increased from $25,351 millions in 2004 to $38,897 millions in 2010. See https://www.nsf.gov/statistics/rdlink/ for the details.

quality-ladder model with international technology transfer. In addition, Chu and Peng (2011) explore the effects of patent breadth in a two-country Schumpeterian growth model, but their study focuses on the interaction between developed countries by considering an environment with two Northern economies, both of which undertake innovative activities. This study, instead, examines the impacts of the same patent tool in the presence of North-South product cycles and international technology transfer via FDI, so our study complements the analysis of Chu and Peng (2011) by focusing on the interaction between developed and developing economies. Furthermore, the current study adds to the above studies by providing a quantitative analysis on the welfare implications of patent breadth, which shows that tightening IPR protection in a country can lead to a sizable welfare improvement in both countries.

Finally, the present paper relates to a large body of empirical studies that examine the relationship between Southern IPR protection and FDI. So far, the results in this strand of literature appear to be very mixed. For example, Primo Braga and Fink (1998) find a negative relationship between the degrees of IPR protection in developing countries and overseas sales by US-based multinationals, whereas Javorcik (2004) and Branstetter *et al.* (2011) find that stronger patent rights in reforming countries have a positive effect on FDI in technology-intensive industries. Additionally, Fosfuri (2004) does not find any significant relationship between the strengths of IPR protection and multinational investment. Thus, our North-South quality ladder model complements these empirical studies by providing a theoretical rationale to support the positive effect of IPR protection in developing countries on FDI.

The rest of this paper is organized as follows. Section 2 introduces the model. Section 3 derives the conditions that determine the steady-state equilibrium and the social welfare functions. Section 4 analytically explores the cross-country effects of patent protection. Section 5 performs a quantitative analysis. Section 6 concludes this study.

2 Model

To analyze the respective effects of Northern patent protection and Southern patent protection, we extend the Dinopoulos and Segerstrom (2010) North-South quality-ladder model with multinational firms, which is a recent variant of the North-South R&D-based model originating from the seminal work by Grossman and Helpman (1991). In the model of Dinopoulos and Segerstrom (2010), a global economy consists of a high-wage North and a low-wage South, and labor, which grows at the same rate in the two countries, is the only factor of production in products and R&D. Firms hire Northern workers to engage in innovative R&D to produce new higher-quality products, and such firms are called *Northern quality leaders* since all their production is located in the North. To take the advantage of lower production costs in the South, a Northern quality leader can transfer its manufacturing operations to the South within multinational firms by hiring Southern workers to engage in adaptive R&D, and such a firm is called a *Southern affiliate* since all its production is located in the South. Adaptive R&D is considered as a measure of FDI because it represents the cost that multinational firms incur to transfer their technology to foreign affiliates. To introduce IPR protection, we incorporate patent breadth to protect producers from the threat of imitations, which determines the price-marginal-cost markup in each intermediate goods market. The level of patent breadth in the North is assumed to be higher than the one in the South to capture the fact that IPR protection in developed countries is generally stronger than that in developing countries.

2.1 Households

At time t, the household in the North (South) has a population size of of L_t^N (L_t^S). For simplicity, we assume that the population growth rates in both countries are identical and equal to $g_L > 0$. Thus, the total population size in the world is $L_t = L_t^N + L_t^S$. Denote by $\alpha \equiv L_t^S / L_t$ the share of Southern population and $1 - \alpha$ the share of Northern population in the global population, respectively.

The lifetime utility function of the representative household in country $i = \{N, S\}$ is given by

$$U \equiv \int_0^\infty e^{-(\rho - g_L)t} \ln c_t^i dt, \tag{1}$$

where $\rho > g_L$ is the discount rate and c_t^i is level of consumption per capita in country i. Each household in country i maximizes (1) subject to the following budget constraint:

$$\dot{a}_t^i = (r_t - g_L)a_t^i + w_t^i - c_t^i \tag{2}$$

where in country i, a_t^i is the real value of financial assets per capita, w_t^i is the real wage rate, and r_t is the real interest rate that households in both countries face at time t. Following Dinopoulos and Segerstrom (2010), we assume that there is a global financial market such that the real interest rates in both countries must be equal. In each country, all prices are expressed in terms of the price of consumption goods.

Solving the standard utility maximization problem gives rise to the familiar Euler equation:

$$\frac{\dot{c}_t^N}{c_t^N} = \frac{\dot{c}_t^S}{c_t^S} = r_t - \rho, \tag{3}$$

which implies that the growth rates of consumption in both countries are identical.

2.2 Final goods

Final goods Y_t are all consumed by households and are produced by perfectly competitive firms that aggregate a unit continuum of intermediate goods $x_t(j)$ using the standard CES aggregator such that

$$Y_t = \left\{ \int_0^1 [x_t(j)]^{\frac{\sigma-1}{\sigma}} dj \right\}^{\frac{\sigma}{\sigma-1}}, \tag{4}$$

where $\sigma > 1$ is the elasticity of substitution between intermediate goods. The market-clearing condition for final goods in the world is

$$Y_t = c_t^N L_t^N + c_t^S L_t^S = [(1-\alpha)c_t^N + \alpha c_t^S]L_t, \tag{5}$$

where $c_t^N L_t^N$ and $c_t^S L_t^S$ are the aggregate consumption in the North and South, respectively. Given zero transportation cost, the law of one price holds such that $p_{c,t}^N = \epsilon_t p_{c,t}^S$, where ϵ_t is the real exchange rate and $p_{c,t}^N$ ($p_{c,t}^S$) is the price of consumption in the North (South). In this study, all variables are expressed in real terms denominated by units of final good that have the same value in the two countries. Solving this profit-maximizing problems yields the demand function for $x_t(j)$ such that

$$x_t(j) = \frac{Y_t}{p_t(j)^\sigma}, \tag{6}$$

where $p_t(j)$ is the price of $x_t(j)$.

2.3 Intermediate goods

The differentiated intermediate goods in each industry $j \in [0,1]$ are produced by a monopolistic quality leader who holds a patent on the latest innovation. This leader's products will not be replaced until a new entrant with a more advanced innovation enters the market, which is known as the *Arrow replacement effect*. Among all intermediate goods, some are produced in the North and the other in the South. If a Northern firm succeeds in inventing a state-of-the-art good, it can register a patent for the good in both the North and the South. Products are mobile across countries, while labor, as the only production factor of intermediate goods, is immobile. The production function of intermediate goods by a quality leader in the North is

$$x_t(j) = z^{n_t(j)} L^N_{x,t}(j) \equiv x^N_t(j) \tag{7}$$

where the parameter $z > 1$ measures the step size of a quality improvement, $n_t(j)$ is the number of quality improvements that have occurred in industry j up to time t, and $L^N_{x,t}(j)$ is the amount of Northern labor employed by the quality leader for manufacturing.

In order to take advantage of cheaper labor force in the South, the quality leader in the North also has an incentive to shift its production to the South. The shift requires adaptive R&D for the Northern quality leader to transfer technology to its foreign affiliate. Without conducting adaptive R&D to modify it to the local market, the production technology possessed by the Northern quality leader can not be used by the foreign producers. Once the technology transfer is complete, the Southern affiliate of the Northern leader can produce intermediate goods as a monopolist according to

$$x_t(j) = \delta z^{n_t(j)} L^S_{x,t}(j) \equiv x^S_t(j) \tag{8}$$

where $\delta > 0$ is a labor-productivity parameter, capturing the productivity of Southern labor relative to Northern labor. $L^S_{x,t}(j)$ is the number of Southern labor employed by the foreign affiliate for production. Notice that with the state-of-the-art technology, the condition for the presence of FDI incentives must hold such that the marginal cost of production in the South has to be smaller than the counterpart in the North, i.e., $w^S_t/(\delta z^{n_t(j)}) < w^N_t/z^{n_t(j)}$.

To analyze the pricing strategy of each category of intermediate goods firms, we examine how these firms operate in equilibrium by taking into account the responses of their potential rivals. First, we consider the case for Northern quality leaders. On the one hand, we assume that IPR protection in the North is incomplete. Therefore, one type of potential rivals for a current Northern quality leader is Northern imitators who are able to gain access to the latest production technology. On the other hand, the current Northern quality leader, as it shifts the production to the South, can make use of cheaper labor in the South where the protection of IPR is weaker. Thus, another type of potential rivals for a current Northern quality leader is the foreign affiliate of the previous Northern leader, who adopt the second-latest-generation production technology that is one step behind the newest one. Moreover, to introduce IPR instruments that can be set by the policymakers, we follow Goh and Olivier (2002) to assume that the strength of IPR protection determines the imitation cost, and define by $\mu_t^N > 1$ the level of patent breadth in the North controlled by Northern patent authority. Accordingly, given the productivity $z^{n_t(j)}$, Northern imitators pay a marginal cost (i.e., $\mu_t^N w_t^N / z^{n_t(j)}$) that is higher than the Northern quality leader's counterpart (i.e., $w_t^N / z^{n_t(j)}$).[13]

Define by $\omega_t \equiv w_t^N / w_t^S$ the relative wage rate. To ensure the existence of two-way product cycles, we impose the following assumption:

Assumption 1. $\omega_t \delta < z/\mu_t^N$.

Specifically, the assumption $\omega_t \delta < z/\mu_t^N$ implies $w_t^S / (\delta z^{n_t(j)-1}) > \mu_t^N w_t^N / z^{n_t(j)} > w_t^N / z^{n_t(j)}$, which means that when the next innovation arrives, the manufacturing process shifts back to the North; both the Northern quality leader and Northern imitators have a cost advantage to win the Southern affiliate of the previous Northern leader.

Then, after the return of production to the North occurs, Assumption 1 indicates that the strongest rival against the Northern leader is Northern imitators. Thus, similar to Iwaisako and Futagami (2013), the breadth of Northern patent protection μ_t^N determines the current Northern quality leader's markup and its maximum (optimal) price. This feature captures the insight in Gilbert and Shapiro (1990) that "breadth as the ability of the patentee to raise price". The standard Bertrand price competition leads to the monopolistic price given by

$$p_t^N(j) = \frac{\mu_t^N w_t^N}{z^{n_t(j)}} \leq \underbrace{\frac{\sigma}{\sigma - 1} \frac{w_t^N}{z^{n_t(j)}}}_{\text{unconstrained price}}, \tag{9}$$

which is the limit price of the Northern leader against the Northern competitive fringes that undertake potential imitations. The unconstrained price is referred to the case in which patent protection in the North is complete and monopolists are able to charge the highest price determined by the intermediate goods market. Consequently, the range of Northern patent breadth is given by $1 < \mu_t^N \leq \sigma/(\sigma - 1)$.

Next, consider the case for the affiliate of the Northern leader who moves the locus of production to the South to make use of a lower wage rate in the South. Define by μ_t^S the level of patent breadth in the South, controlled by Southern patent authority. In this study, we assume that patent protection in the North is stricter than in the South such that $\mu^S < \mu^N$.[14] Hence, incomplete patent protection in the South attracts Southern imitators who also get access to the latest-generation technology. In this case, the most competitive rival for this affiliate is Southern imitators, since given the previously stated condition $\omega_t \delta > 1$, the marginal cost of Southern imitators is lower than that of Northern imitators (i.e., $\mu_t^S w_t^S / (\delta z^{n_t(j)}) < \mu_t^N w_t^N / z^{n_t(j)}$).[15] Never-

[13] See Li (2001) for the detailed discussion on incomplete patent breadth in a quality-ladder growth model.

[14] According to Dinopoulos and Kottaridi (2008), the average level of patent protection in developed countries was roughly 33% higher than the counterpart in developing countries during 1960-2000.

[15] In addition, Assumption 1 implies that when technology transfer is completed, the marginal cost of the Southern affiliate of the previous leader (i.e., $w_t^S / (\delta z^{n_t(j)-1})$) is larger than that of Northern imitators' (i.e., $\mu_t^N w_t^N / (\delta z^{n_t(j)})$), making Southern imitators the strongest rival against the Southern affiliate of the current leader.

theless, the current affiliate is protected the policy of Southern patent authority because it enters the Southern market through adaptive innovation. Accordingly, similar to the pricing strategy of the Northern leader, the highest price set by the Southern affiliate is given by

$$p_t^S(j) = \frac{\mu_t^S w_t^S}{\delta z^{n_t(j)}} < \underbrace{\frac{\sigma}{\sigma-1}\frac{w_t^S}{\delta z^{n_t(j)}}}_{\text{unconstrained price}}, \tag{10}$$

where the range of Southern patent breadth is $1 < \mu_t^S < \sigma/(\sigma-1)$.

Define the aggregate quality index across industries $j \in [0,1]$ as

$$Q_t \equiv \int_0^1 q_t(j)dj, \tag{11}$$

where $q_t(j) = [z^{n_t(j)}]^{\sigma-1}$. It is also the average quality index given a unit measure of intermediate goods industries in the global economy. The labor demands for an average-quality product produced by a Northern leader and a Southern affiliate can be expressed, respectively, by

$$\bar{L}_{x,t}^N = \int_0^1 L_{x,t}^N(j)dj = Q_t Y_t \left(\mu_t^N w_t^N\right)^{-\sigma}, \tag{12}$$

$$\bar{L}_{x,t}^S = \int_0^1 L_{x,t}^S(j)dj = \frac{Q_t Y_t}{\delta}\left(\frac{\delta}{\mu_t^S w_t^S}\right)^{\sigma}. \tag{13}$$

Using these equations, we can express the labor demands for product j as

$$L_{x,t}^N(j) = \frac{q_t(j)}{Q_t}\bar{L}_{x,t}^N; \quad L_{x,t}^S(j) = \frac{q_t(j)}{Q_t}\bar{L}_{x,t}^S. \tag{14}$$

The instantaneous profit of the Northern leader is

$$\pi_t^N(j) = p_t^N(j)x_t^N(j) - w_t^N(j)L_{x,t}^N(j) = \left(\mu^N - 1\right) q_t(j)\frac{w_t^N Y_t}{(\mu_t^N w_t^N)^{\sigma}}, \tag{15}$$

where we have applied (7), (8), (12), and (13). Furthermore, the monopoly profit of the Southern affiliate of the Northern leader is

$$\pi_t^S(j) = p_t^S(j)x_t^S(j) - w_t^S L_{x,t}^S(j) = \left(\mu_t^S - 1\right) q_t(j)\frac{w_t^S Y_t}{\delta}\left(\frac{\delta}{\mu_t^S w_t^S}\right)^{\sigma}, \tag{16}$$

where again (7), (8), (12), and (13) are used.[16]

To ensure that moving the locus of production to the South is attractive to the Northern leader

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[16]Given the production technology $z^{n_t(j)}$ in the market, the profit flow of a new Northern quality leader in industry j by successfully bringing the more advanced technology $z^{n_t(j)+1}$ is $z^{\sigma-1}\left(\mu_t^N - 1\right) q_t(j) w_t^N Y_t/(\mu_t^N w_t^N)^{\sigma}$. This profit has to exceed the Southern affiliate's profit $\pi_t^S(j)$ for the return of production to the North to occur, implying $(\delta\omega_t)/z < \Psi_t$, where $\Psi_t \equiv \{[(\mu_t^N - 1)(\mu_t^S)^{\sigma}]/[(\mu_t^S - 1)(\mu_t^N)^{\sigma}\}^{1/(\sigma-1)}$. This condition is indeed guaranteed by Assumption 1, since $\Psi_t \in (1,\infty)$ for $\mu_t^S \in (1, \mu_t^N)$, which ensures $\delta\omega_t < 1/\mu_t^N < \Psi_t$ to hold.

such that $\pi_t^S(j) > \pi_t^N(j)$, the following assumption is imposed:

Assumption 2. $\delta\omega_t > \left[\frac{(\mu_t^N-1)(\mu_t^S)^\sigma}{(\mu_t^S-1)(\mu_t^N)^\sigma}\right]^{\frac{1}{\sigma-1}}$.

This assumption implies that the benefit of shifting production to the South with a lower wage rate, after taking into account the labor productivity difference δ, must compensate for the potential loss due to a lower degree of patent protection in the South.

2.4 Innovative and adaptive R&D

Innovative R&D is all performed by entrepreneurs in the North. By employing an amount of $L_{r,t}^N(j)$ of Northern labor to engage in innovative R&D in industry j, an R&D entrepreneur will succeed in inventing a newer generation of product in the industry with an instantaneous probability

$$\lambda_t^N(j) = \frac{Q_t^\xi L_{r,t}^N(j)}{\beta q_t(j)}, \tag{17}$$

where the term $Q_t^\xi/[\beta q_t(j)]$ represents the productivity in innovative R&D. $\beta > 0$ is an exogenous parameter. $q_t(j)$ reflects the decrease in the productivity of R&D labor as the product quality increases. The consideration of decreasing R&D labor productivity (i.e., the increasing research complexity) follows the theoretical studies such as Segerstrom (1998) and Segerstrom (2000) and is consistent with recent empirical findings from Webb *et al.* (2017), which eliminates the counterfactual scale effects.[17] In addition, to facilitate our quantitative analysis in Section 5, Q_t^ξ is introduced to capture the intertemporal knowledge spillover effect, and the parameter $\xi \in [0, 1)$ measures the degree of this externality.

The expected value of owning the most recent innovation in industry j is denoted by $v_t^N(j)$. The free entry into R&D implies the following zero-expected profit condition for innovative R&D:

$$v_t^N(j)\lambda_t^N(j) = w_t^N L_{r,t}^N(j) \Leftrightarrow v_t^N(j) = \beta w_t^N q_t(j) Q_t^{-\xi}, \tag{18}$$

where we have used (17).

Adaptive R&D in the South is performed by local entrepreneurs and the Southern affiliates of Northern industry leaders. By employing $L_{r,t}^S(j)$ units of Southern labor into adaptive R&D, the Southern affiliate of a Northern leader in industry j will succeed in shifting the production to the Southern affiliate with an instantaneous probability

$$\lambda_t^S(j) = \frac{Q_t^\xi L_{r,t}^S(j)}{\gamma q_t(j)}, \tag{19}$$

where $Q_t^\xi/[\gamma q_t(j)]$ measures the labor productivity in adaptive innovation. $\gamma > 0$ is an exogenous parameter. Similar to the process in innovative R&D, $q_t(j)$ in the denominator of (19) reflects the increasing research complexity, and Q_t^ξ captures the intertemporal knowledge spillover effect. Denote by $v_t^S(j)$ the firm value of the Southern affiliate of a Northern leader. Thus, the expected

[17] See Jones (1999) for a detailed discussion on how semi-endogenous growth models remove scale effects.

net profit for the Northern quality leader to invest in adaptive R&D is $v_t^S(j) - v_t^N(j)$. The free-entry condition implies the zero-expected profit for adaptive R&D, which can be expressed as

$$\left[v_t^S(j) - v_t^N(j)\right] \lambda_t^S(j) = w_t^S L_{r,t}^S(j) \Leftrightarrow v_t^S(j) - v_t^N(j) = \gamma w_t^S q_t(j) Q_t^{\xi}, \tag{20}$$

where (19) is applied.

Moreover, we follow the standard treatment in this class of models to focus on a symmetric equilibrium in which $\lambda_t^N(j) = \lambda_t^N$ and $\lambda_t^S(j) = \lambda_t^S$.[18]

2.5 Stock market

The Hamilton-Jacobi-Bellman equation for $v_t^N(j)$ is

$$r_t v_t^N(j) = \pi_t^N(j) - w_t^S L_{r,t}^S(j) - \lambda_t^N(j) v_t^N(j) + \lambda_t^S(j)[v_t^S(j) - v_t^N(j)] + \dot{v}_t^N(j),$$

which is also the no-arbitrage condition that determines the value of $v_t^N(j)$. In equilibrium, the return on the asset $v_t^N(j)$, $r_t v_t^N(j)$ on the left-hand-side (LHS), equals the sum of the terms on the right-hand-side (RHS), including (i) the flow profits $\pi_t^N(j)$; (ii) the expenditure for adaptive R&D $w_t^S L_{r,t}^S(j)$; (iii) the expected capital loss due to creative destruction $\lambda_t^N(j) v_t^N(j)$; (iv) the expected capital gain once adaptive R&D is successful $\lambda_t^S(j)[v_t^S(j) - v_t^N(j)]$; (v) the potential capital gain $\dot{v}_t^N(j)$. Using (20), the above equation is reduced to

$$r_t v_t^N(j) = \pi_t^N(j) - \lambda_t^N(j) v_t^N(j) + \dot{v}_t^N(j). \tag{21}$$

Similarly, the no-arbitrage condition that determines the value of $v_t^S(j)$ is given by

$$r_t v_t^S(j) = \pi_t^S(j) - \lambda_t^N(j) v_t^S(j) + \dot{v}_t^S(j). \tag{22}$$

The LHS of this equation is also the return on the asset $v_t^S(j)$, and this asset return is the sum of the terms on the RHS including (i) monopolistic profits as an affiliate $\pi_t^S(j)$; (ii) expected capital loss because of creative destruction $\lambda_t^N(j) v_t^S(j)$; (iii) potential capital gains $\dot{v}_t^S(j)$.

2.6 Decentralized equilibrium

Definition 1. *The equilibrium is defined as a time path of prices, $\{r_t, w_t^N, w_t^S, p_t^N(j), p_t^S(j), v_t^N, v_t^S\}_{t=0}^{\infty}$, a time path of allocations, $\{c_t^N, c_t^S, Y_t, x_t^N(j), x_t^S(j), L_{x,t}^N(j), L_{x,t}^S(j), L_{r,t}^N(j), L_{r,t}^S(j)\}_{t=0}^{\infty}$, for $j \in [0,1]$, and a time path of patent policies $\{\mu_t^N, \mu_t^S\}_{t=0}^{\infty}$.*

Moreover, at each instance of time,

• the representative household in the North maximizes lifetime utility taking $\{r_t, P_t, w_t^N\}$ as given;

• the representative household in the South maximizes lifetime utility taking $\{r_t, P_t, w_t^S\}$ as given;

[18] Cozzi *et al.* (2007) provide a theoretical justification for the symmetric equilibrium in this strand of Schumpeterian growth model. See Chu *et al.* (2018) for the same treatment in a monetary Schumpeterian growth model with North-South technology transfer.

• competitive final goods firms produce Y_t to maximize profits taking $\{p_t^N(j), p_t^S(j)\}$ as given;
• Northern quality leaders choose $p_t^N(j)$ and produce $x_t^N(j)$ to maximize profits taking w_t^N as given;
• Southern affiliates choose $p_t^S(j)$ and produce $x_t^S(j)$ to maximize profits taking w_t^S as given;
• entrepreneurs in the North employ $L_{r,t}^N(j)$ to perform innovative R&D taking $\{r_t, w_t^N, v_t^N\}$ as given;
• Southern affiliates of Northern quality leaders employ $L_{r,t}^S(j)$ to perform adaptive R&D taking $\{r_t, w_t^S, v_t^S\}$ as given;
• the final goods market clears such that $Y_t = c_t^N L_t^N + c_t^S L_t^S$;
• the labor market clearing conditions hold in both countries; and
• the nominal exchange rate is determined by the law of one price such that $\epsilon_t = p_{c,t}^N / p_{c,t}^S$.

3 Steady-state equilibrium

In this section, we solve the steady-state equilibrium and analyze how a stationary time path of Southern and Northern patent policy (i.e., $\{\mu^S, \mu^N\}$) affects innovation in the North and international technology transfer, respectively. To do so, we first derive the steady-state number of each type of industries and the expression of quality index. Then, we specify the steady-state labor market conditions in the two countries, and by combining these conditions we construct the Southern and Northern steady-state conditions of technology transfer and innovation. Finally, we derive the steady-state welfare in both countries.

3.1 Industry composition and quality dynamics

There are two types of industries in the intermediate goods sector, the Northern quality leaders and the Southern affiliates. Denote θ^N and θ^S as the steady-state measure of these two types of industries, respectively. Then, these measures of all industries must add up to one such that

$$\theta^N + \theta^S = 1. \tag{23}$$

Each industry can switch randomly across these two categories with probabilities that in turn depends on the Poisson arrival rates of innovative and adaptive R&D. In the steady state, the measure of industries in each type must be constant such that the flow in and out of the Southern affiliate must be equal. This relation can be established as the following equation

$$\underbrace{\theta^N \lambda^S}_{\text{flow into affiliates}} = \underbrace{\theta^S \lambda^N}_{\text{flow out of affiliates}}. \tag{24}$$

It is straightforward that this equation can be also stated as the flow out and into the Northern quality leaders. Solving (23) and (24) yields the measure of these industries such that

$$\theta^N = \frac{\lambda^N}{\lambda^N + \lambda^S}, \tag{25}$$

$$\theta^S = \frac{\lambda^S}{\lambda^N + \lambda^S}. \tag{26}$$

By definition, the aggregate quality index across industries $j \in [0, 1]$ is

$$Q_t \equiv \int_0^1 q_t(j)dj = \int_0^1 \kappa^{n_t(j)}dj, \tag{27}$$

where $\kappa \equiv z^{\sigma-1} > 1$ is a composite parameter that is increasing in the quality step size z. This quality index can be further decomposed into the following two components:

$$Q_t = Q_t^N + Q_t^S = \int_{\theta^N} q_t(j)dj + \int_{\theta^S} q_t(j)dj. \tag{28}$$

The following lemma provides the steady-state expression for the measure of each component of aggregate quality.

Lemma 1. *In the steady state, the two components of aggregate quality can be expressed as*

$$\frac{Q_t^N}{Q_t} = \frac{\kappa\lambda^N}{\kappa\lambda^N + \lambda^S}, \tag{29}$$

$$\frac{Q_t^S}{Q_t} = \frac{\lambda^S}{\kappa\lambda^N + \lambda^S}. \tag{30}$$

Proof. See Appendix A.1. □

3.2 Northern labor market

The labor market clearing condition in the North is given by

$$L_t^N = L_{x,t}^N + L_{r,t}^N = \int_{\theta^N} L_{x,t}^N(j)dj + \int_0^1 L_{r,t}^N(j)dj. \tag{31}$$

The amount of labor employed for production by Northern quality leaders is

$$L_{x,t}^N = \int_{\theta^N} \frac{q_t(j)}{Q_t}\bar{L}_{x,t}^N dj = \frac{Q_t^N}{Q_t}\bar{L}_{x,t}^N, \tag{32}$$

where the first equality uses (14). Using (17), the amount of labor employed for innovative R&D is

$$L_{r,t}^N = \beta\lambda^N Q_t^{1-\xi}, \tag{33}$$

where the symmetry condition $\lambda^N(j) = \lambda^N$ is imposed. Substituting (32) and (33) into (31), together with (29), yields the Northern labor market clearing condition in per capita terms such that

$$1 = \frac{\bar{L}_{x,t}^N}{L_t^N}\frac{\kappa\lambda^N}{\kappa\lambda^N + \lambda^S} + \beta\lambda^N\Phi, \tag{34}$$

where $\Phi_t \equiv Q_t^{1-\xi}/L_t^N = \Phi$ is defined as the average quality per Northern worker, which is constant over time in any steady-state equilibrium.

3.3 Southern labor market

The labor market clearing condition in the South is given by

$$L_t^S = L_{x,t}^S + L_{r,t}^S = \int_{\theta^S} L_{x,t}^S(j)dj + \int_{\theta^N} L_{r,t}^S(j)dj. \tag{35}$$

The amount of labor employed for production by Southern affiliates is

$$L_{x,t}^S = \int_{\theta^S} \frac{q_t(j)}{Q_t} \bar{L}_{x,t}^S dj = \frac{Q_t^S}{Q_t} \bar{L}_{x,t}^S, \tag{36}$$

where the first equality uses (14). Using (19) and imposing the symmetry condition $\lambda_t^S(j) = \lambda^S$, the amount of labor employed for adaptive R&D is given by

$$L_{r,t}^S = \gamma \lambda^S Q_t^{1-\xi} \frac{Q_t^N}{Q_t}. \tag{37}$$

Substituting (36) and (37) into (35), coupled with (29) and (30), we express the Southern labor market clearing condition in per capita terms such that

$$1 = \frac{\lambda^S}{\kappa \lambda^N + \lambda^S} \left[\frac{\bar{L}_{x,t}^S}{L_t^S} + \frac{\gamma \kappa \lambda^N (1-\alpha)}{\alpha} \Phi \right], \tag{38}$$

where $L_t^N / L_t^S = (1-\alpha)/\alpha$ is used.

3.4 Innovation and technology transfer

Differentiating (27) with respect to time t yields the growth rate of the quality index

$$\dot{Q}_t = \int_0^1 \left[\kappa^{n_t(j)+1} - \kappa^{n_t(j)} \right] \lambda_t^N dj = (\kappa - 1) \lambda_t^N Q_t. \tag{39}$$

Taking the log of $\Phi_t = Q_t^{1-\xi} / L_t^N$ and differentiating it with respect to time yields

$$\frac{\dot{\Phi}_t}{\Phi_t} = (1-\xi)\frac{\dot{Q}_t}{Q_t} - \frac{\dot{L}_t^N}{L_t^N} = (1-\xi)(\kappa-1)\lambda_t^N - g_L. \tag{40}$$

Since Φ_t is stationary in the steady state, (40) implies that the steady-state arrival rate of innovation is completely determined by the exogeneous population growth rate given by

$$\lambda^N = \frac{g_L}{(1-\xi)(\kappa-1)}. \tag{41}$$

This feature originates from the insight that the increasing research complexity acts as a counteractive force to growing R&D inputs. As discussed in Segerstrom (2000) and Dinopoulos and Segerstrom (2010), any increase in R&D inputs leading to a higher product quality makes product more complex and harder for researchers to find further improvements. As a consequence, a growing R&D labor employment is required to maintain a constant innovation rate over time. In the model, R&D labor is only determined by the exogenous population growth rate, which leads the steady-state arrival rate of innovation to be exogenously pinned down.

Furthermore, in the steady state, from (21) and (22), the values of assets for the Northern quality leader and the Southern affiliate can be expressed as

$$v_t^N(j) = \frac{\pi_t^N(j)}{\rho + \lambda^N}, \tag{42}$$

and

$$v_t^S(j) = \frac{\pi_t^S(j)}{\rho + \lambda^N}. \tag{43}$$

Substituting (15) and (42) into (18) yields the following *steady-state innovative R&D condition*:

$$\left(\mu^N - 1\right) \frac{\bar{L}_{x,t}^N}{Q_t^{1-\xi}} = \beta(\rho + \lambda^N). \tag{44}$$

Similarly, substituting (15), (16), (42), and (43) into (20) gives rise to the following *steady-state adaptive R&D condition*:

$$\left(\mu^S - 1\right) \frac{\bar{L}_{x,t}^S}{Q_t^{1-\xi}} - \omega \left(\mu^N - 1\right) \frac{\bar{L}_{x,t}^N}{Q_t^{1-\xi}} = \gamma(\rho + \lambda^N), \tag{45}$$

where $\omega = w_t^N / w_t^S$ is the steady-state relative wage, which will be shown to be a function of the patent instruments $\{\mu^N, \mu^S\}$ in the next section.

Next, substituting (44) into (34) yields the *Northern steady-state condition* such that

$$1 = \beta\lambda^N \Phi \left\{ \frac{\kappa(\rho + \lambda^N)}{(\mu^N - 1)(\kappa\lambda^N + \lambda^S)} + 1 \right\}, \tag{46}$$

which contains two endogenous variables $\{\Phi, \lambda^S\}$ and features a positive slope and a positive Φ-intercept in the $\{\Phi, \lambda^S\}$ space as shown in Figure 1, where "North" represents the Northern steady-state condition. The intuition behind the positive slope of the Northern steady-state condition can be explained as follows. At each instant of time, an increase in λ^S implies that more products are manufactured in the South but less in the North, which in turn leads to a reallocation of labor in the North from production to innovative R&D due to the resource constraint on Northern labor. Thus, the increase in Northern R&D labor raises the average quality per Northern worker (i.e., Φ) in the steady state.

Then, substituting (44) into (38), together with (45), yields the *Southern steady-state condition* such that

$$1 = \frac{\Phi\lambda^S(1 - \alpha)}{\alpha(\kappa\lambda^N + \lambda^S)} \left\{ \frac{(\rho + \lambda^N)\left[\gamma + \beta\omega\left(\mu^N, \mu^S\right)\right]}{\mu^S - 1} + \gamma\kappa\lambda^N \right\}, \tag{47}$$

where the relation $L_t^N / L_t^S = (1 - \alpha)/\alpha$ is used. This condition also contains two endogenous variables $\{\Phi, \lambda^S\}$ but features a negative slope, with no intercepts, in the $\{\Phi, \lambda^S\}$ space in Figure

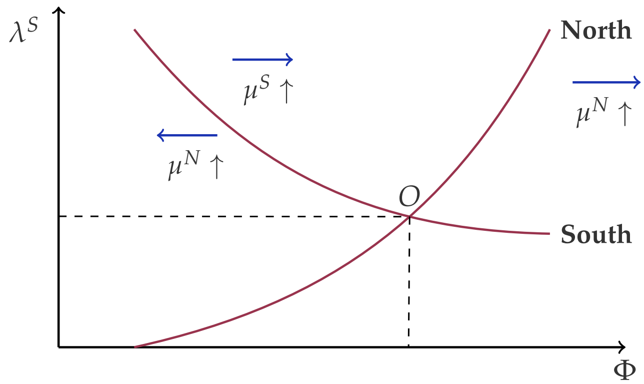

Figure 1: The steady-state equilibrium.

1, where "South" represents the Southern steady-state condition. Intuitively, at each instant of time, an increase in λ^S implies that more products are manufactured in the South, which in turn reallocates labor in the South from adaptive R&D to production due to the resource constraint on Southern labor. Therefore, according to (37) that shows the level of adaptive R&D labor (i.e., $L_r^S = \gamma\kappa L_t^N \Phi \lambda^N \lambda^S / (\kappa\lambda^N + \lambda^S)$), a higher λ^S can be consistent with a smaller L_r^S only when the difficulty level $\Phi = Q^{1-\xi}/L^N$ decreases sufficiently (i.e., technologies become sufficiently easy to be transferred to the South). Summing up, (46) and (47) are the two conditions that implicitly solve for the steady-state values of $\{\Phi, \lambda^S\}$. The intersection at point O in Figure 1 determines the unique steady-state values for Φ and λ^S.

3.5 Social welfare

In this section, we derive the steady-state social welfare in each country.[19] Imposing balanced growth on (1) yields the steady-state welfare of the Northern household given by

$$U^N = \frac{1}{\rho - g_L}\left(\ln c_0^N + \frac{g}{\rho - g_L}\right), \tag{48}$$

where $g = g_L/[(1-\xi)(\sigma-1)]$ is the growth rate of consumption (as well as final goods) per capita, which depends on exogenous parameters due to the semi-endogenous growth property. Therefore, the steady-state level of welfare is determined by the balanced-growth level of consumption. According to (2), using balanced growth condition $\dot{a}_t^N / a_t^N = g$ yields

$$c_t^N = (\rho - g_L)\, a_t^N + w_t^N. \tag{49}$$

The balanced-growth level of consumption c_0^N is thus a sum of asset income $(\rho - g_L)a_0^N$ and wage income w_0^N. Similar conditions also apply to the Southern case. To explicitly derive a_0^N and a_0^S, we follow Dinopoulos and Segerstrom (2010) to assume that the asset from innovative R&D in

[19] A more complete welfare analysis should take into account the dynamic transition of the household's utility from the initial steady state to the final one. However, such an analysis is much more challenging both analytically and numerically in this class of models. Therefore, the welfare analysis in this study follows the usual treatment in the literature to focus on steady-state welfare. See, for example, Acemoglu and Akcigit (2012) and Chu *et al.* (2018).

the North is owned by the Northern household whereas the asset from adaptive R&D in the South is owned by the Southern household. Under this assumption, we show in Lemma 2 that the balanced-growth levels of consumption $\{c_0^N, c_0^S\}$ can be expressed as a function of $\{w_0^N, w_0^S\}$, as similar to Chu *et al.* (2018).

Lemma 2. *The balanced-growth level of consumption can be expressed as*

$$c_0^N = \underbrace{\beta(\rho - g_L)\Phi w_0^N}_{\text{asset income}} + \underbrace{w_0^N}_{\text{wage income}} = w_0^N I^N, \tag{50}$$

$$c_0^S = \underbrace{(\rho - g_L)(\gamma + \beta\omega)\frac{\kappa\lambda^N \Phi(1-\alpha)}{\alpha(\kappa\lambda^N + \lambda^S)} w_0^S}_{\text{asset income}} + \underbrace{w_0^S}_{\text{wage income}} = w_0^S I^S, \tag{51}$$

$$w_0^S = \left(\Phi L_0^N\right)^{\frac{1}{(1-\xi)(\sigma-1)}} \left\{ \underbrace{\left(\mu^N \omega\right)^{1-\sigma} \frac{\kappa\lambda^N}{\kappa\lambda^N + \lambda^S}}_{\text{quality leaders}} + \underbrace{\left(\frac{\mu^S}{\delta}\right)^{1-\sigma} \frac{\lambda^S}{\kappa\lambda^N + \lambda^S}}_{\text{affiliates}} \right\}^{\frac{1}{\sigma-1}}, \tag{52}$$

where $\{I^N, I^S\}$ denote the consumption-wage ratio for the North and South.

Proof. See Appendix A.2. □

Due to the complexity of the analytical welfare analysis, we perform a quantitative analysis to examine the effects of both Southern and Northern IPR protection on steady-state welfare in Section 5.

4 Patent policy, innovation, and technology transfer

In this section, we explore the effects of Southern and Northern patent policy $\{\mu^S, \mu^N\}$ on the innovation rate λ^N and the technology transfer rate λ^S, respectively. Before doing so, we examine the effects of these patent-policy tools on the relative wage ω. From (12) and (13), we obtain

$$\frac{\bar{L}_{x,t}^S}{Q_t} = \frac{1}{\delta}\left(\frac{\delta\mu^N\omega}{\mu^S}\right)^{\sigma} \frac{\bar{L}_{x,t}^N}{Q_t}. \tag{53}$$

Dividing (44) by (45) and making use of (53) yield the following *steady-state relative-wage condition*:

$$\frac{\gamma}{\beta\omega^\sigma} + \omega^{1-\sigma} = \delta^{\sigma-1}\left(\frac{\mu^N}{\mu^S}\right)^{\sigma} \frac{\mu^S - 1}{\mu^N - 1}, \tag{54}$$

which is an implicit function that pins down the steady-state equilibrium value of the relative wage $\omega(\mu^N, \mu^S)$. The following proposition shows the effects of patent policy in each country on the relative wage.

Proposition 1. *Strengthening patent protection in the South lowers the relative wage rate between the North and the South, whereas strengthening patent protection in the North raises the relative wage rate.*

Proof. See Appendix A.3. □

Proposition 1 can be explained as follows. As shown in (16), strengthening Southern patent protection grants a larger market power to Southern affiliates by allowing them to charge a higher markup. Given the wage rates, this raises the benefits of being Southern affiliates, which increases the incentives for adaptive innovation. Thus, the value of Southern firms $v_t^S(j)$ as indicated in (43) (relative to the value of Northern firms as indicated in (42)) tends to rise. Then, the zero-profit condition for adaptive R&D in (20) implies that the increase in the reward for adaptive R&D must correspondingly cause an increase in the R&D cost. This yields a positive effect on the demand for Southern R&D labor. Consequently, strengthening Southern patent protection raises the wage rate in the South relative to the North.

By contrast, given the wage rates, strengthening Northern patent protection raises the benefits of remaining as a Northern quality leader through a higher markup. This decreases the incentives for adaptive R&D, and the firm value $v_t^S(j)$ as shown in (43) (relative to the value of Northern firms as shown in (42)) tends to decline. According to the zero-profit condition for adaptive R&D in (20), a decrease in the reward for adaptive R&D corresponds to a decrease in the R&D cost, yielding a negative effect on the demand for Southern R&D labor. Therefore, strengthening Northern patent protection reduces the wage rate in the South relative to the North.

Having established the effects of Southern and Northern patent policy $\{\mu^S, \mu^N\}$ on the relative wage rate ω, we are now in position to explore their effects on the rate of innovation λ^N and of international technology transfer λ^S. First, the following proposition illustrates the results regarding the impacts of an increase in μ^S on λ^N and λ^S.

Proposition 2. *Strengthening patent protection in the South yields (i) a temporary higher rate of innovation in the North, and (ii) a positive effect on the technology transfer from the North to the South.*

Proof. See Appendix A.4. □

Proposition 2 can be explained as follows. Graphically, a higher μ^S shifts the South curve to the right in Figure 1, whereas this shift does not affect the North curve, leading to a rise in both Φ and λ^S. Intuitively, a rise in μ^S increases the profit margin of the Southern affiliate in (16). This makes it more attractive for firms to engage in adaptive R&D in the South by changing the relative asset values. To see this, combining (18) and (20), and substituting (54) into the resulting equation yield

$$\frac{v_t^S(j)}{v_t^N(j)} = \frac{\pi_t^S(j)}{\pi_t^N(j)} = \left(\frac{\gamma}{\beta}\right)\frac{1}{\omega(\mu^N, \mu^S)} + 1, \tag{55}$$

where (42) and (43) are used in the first equality and (15), (16), and (54) are used in the second equality. Recall that a higher μ^S decreases the relative wage rate ω; therefore, it also increases $v_t^S(j)/v_t^N(j)$. In this case, more adaptive R&D will be performed, so a higher μ^S yields a positive effect on the rate of international technology transfer λ^S. Moreover, the higher rate of technology transfer to the South implies a smaller number of products being manufactured in the North. The lower demand for Northern production labor causes a reallocation of labor in the North from manufacturing to innovative R&D. As a consequence, the rate of Northern innovation λ^N increases in the short run, which is associated with a higher average quality per Northern worker Φ in the long run, as implied by (40).

Next, the following proposition illustrates the results regarding the impacts of an increase in μ^N on λ^N and λ^S.

Proposition 3. *Strengthening patent protection in the North yields (i) a temporary higher (lower) rate of innovation in the North if the Southern population size is sufficiently small (large), and (ii) a lower rate of technology transfer from the North to the South.*

Proof. See Appendix A.5. □

Proposition 3 can be explained as follows. Figure 1 shows that a higher μ^N shifts the North curve to the right whereas it shifts the South curve to the left, resulting in an unambiguously decreasing effect on λ^S and an ambiguous effect on Φ.[20] Intuitively, as for the impact on λ^S, a higher μ^N increases the profit margin of the Northern quality leaders through allowing for a higher markup in (15). This increases the innovative R&D firm value relative to the adaptive R&D firm value (i.e., $v_t^S(j)/v_t^N(j)$ declines), as explained in Proposition 2.[21] In other words, conducting adaptive R&D becomes less attractive. Thus, less international technology transfer occurs (i.e., a lower λ^S) under a stronger degree of Northern patent protection (i.e., a higher μ^N).

As for the effect on Φ, one can see from (15) that, a strengthened Northern patent protection μ^N causes two contrasting effects as follows. On the one hand, as aforementioned, a larger μ^N increases the profit margin of Northern quality leaders, which increases the incentives for innovative R&D. This tends to reallocate labor from production to R&D in the North. On the other hand, a larger μ^N decreases the technology transfer rate λ^S (according to Proposition 3 (ii)), which implies that more products will be manufactured in the North. This tends to reallocate labor from R&D to production in the North. Accordingly, whether a larger Northern patent breadth μ^N increases the average quality per Northern worker Φ in the long run depends on the interplay between the positive effect of μ^N on Northern R&D labor through markup and the negative effect through product manufacturing.

We find that this interplay is determined by the Southern population size α. To see this, we use $\lambda_t^S(j) = \lambda_t^S$ and (37) to derive

$$\lambda_t^S = \frac{L_{r,t}^S}{\gamma Q_t^N} = \frac{1}{\gamma\Phi}\frac{L_{r,t}^S}{(1-\alpha)L_t}\frac{Q_t}{Q_t^N}, \tag{56}$$

where the second equality uses $\Phi = Q_t/L_t^N$ and $L_t^N = (1-\alpha)L_t$. In the steady state, Q_t^N/Q_t is given by (29), and hence, (56) can be reexpressed as

$$\Phi = \frac{1}{\gamma}\underbrace{\frac{\kappa\lambda^N + \lambda^S(\mu^N)}{\kappa\lambda^N\lambda^S(\mu^N)}}_{A}\underbrace{\frac{L_{r,t}^S}{(1-\alpha)L_t}}_{B}, \tag{57}$$

where A is decreasing in λ^S. Consider that λ^S is a function of μ^N in the steady-state equilibrium. In this case, A captures the positive effect of μ^N on Φ by increasing the Northern quality leaders'

[20]Precisely, if an increase in μ^N shifts the North curve to the right in a larger (smaller) magnitude than the South curve to the left, then an increase (decrease) in Φ emerges in response.

[21]Similarly, combining (18) and (20) yields $v_t^S(j)/v_t^N(j) = (\gamma/\beta)/\omega(\mu^N, \mu^S) + 1$, which shows that $v_t^S(j)/v_t^N(j)$ is decreasing in μ^N.

profit margin, given that an increase in μ^N decreases λ^S and increases A and Φ. Nevertheless, B captures the negative effect of μ^N on Φ by increasing the Northern labor demand in product manufacturing, given that an increase in μ^N decreases $L^S_{r,t}$, and thus B and Φ.

Therefore, one can see that, when the size of Southern population α is sufficiently small, the decrease in the number of products manufactured by Southern affiliates is not significant, implying a small increase in the Northern manufacturing operations. Hence, the negative effect B via products manufacturing becomes relatively weak to be dominated by the positive effect A via markup, causing a reallocation of labor in the North from manufacturing to innovative R&D. As a result, the rate of Northern innovation λ^N increases in the short run, and the average quality per Northern worker Φ increases in the long run, as implied by (40). By contrast, if the size of Southern population α is sufficiently large, the decrease in the number of products manufactured by Southern affiliates is significant. In this case of a large increase in the Northern manufacturing operations, the negative effect B through product manufacturing becomes relatively strong to dominate the positive effect A through markup. Consequently, the resulting mechanism reverses; the rate of Northern innovation λ^N decreases in the short run, and the average quality per Northern worker Φ decreases in the long run.

5 Quantitative analysis

In this section, we calibrate our model to numerically evaluate the effects of the Northern and Southern patent instruments, respectively. Specifically, we consider China as the South and the US as the North to explore the welfare implications of patent protection in each country. To do so, we first describe the calibration strategy in Section 5.1. Section 5.2 then provides the benchmark quantitative results, and Section 5.3 shows the results of robustness checks by altering the values of some parameters and empirical moments.

5.1 Calibration

To perform this numerical analysis, the strategy is to assign steady-state values to the following structural parameters $\{\rho, \sigma, \alpha, \mu^N, \mu^S, \delta, \kappa, \beta, \gamma, z, \xi\}$. We follow Acemoglu and Akcigit (2012) to choose a value of 0.05 for the discount rate ρ. We follow Acemoglu *et al.* (2018) to capture the empirical estimates of Broda and Weinstein (2006) who show that the elasticity of substitution σ is roughly 2.9. Using the data from the World Development Indicators on the labor force size of the US and China, the parameter α is set to 0.829 to correspond to the relative population size.[22] As for the market-level values of the Northern patent instrument μ^N and the Southern instrument μ^S, we choose $\mu^N = 1.3$ according to the estimates of average markup ratio for the US in Christopoulou and Vermeulen (2012)[23] and $\mu^S = 1.25$ according to the estimates for China in Lu and Yu (2015).[24] As for the North-South relative wage rate ω, it is about 20.101 from 2002 to 2013 according to the data from the Conference Board on manufacturing hourly compensation costs

[22] The data is available at http://wdi.worldbank.org/tables, Table 2.2, Labor Force Structure.

[23] See also Norrbin (1993) who reports a similar estimate.

[24] Using the data from the Annual Survey of Industrial Production (ASIP), Lu and Yu (2015) show that the average markup of most Chinese two-digit manufacturing industries is approximately between 1 and 1.3, and we choose a value of 1.25 within this range.

between the US and China.[25] Then, we choose a value of $\delta = 0.0625$ to ensure that Assumptions 1 and 2 are satisfied given the parameter values chosen above.

As for κ, γ, and β, given that it is the relative R&D productivity γ/β (rather than their individual values) that determines the values of variables in equilibrium, we then only need to calibrate κ and γ/β by using (i) the population growth rate; (ii) the innovation arrival rate; and (iii) the relative R&D intensity for both the US and China.[26] For g_L, we follow Jones and Williams (2000) to set it to 1.44% to correspond to the long-run growth rate of the US labor force. For λ^N, we select an empirically plausible value of 5% and explore the other values in the robustness analysis.[27] For the relative R&D intensity, according to the OECD database, the gross domestic spending on R&D for the US and China is about 2.596% and 1.226% of their respective GDP.[28] Based on this relative R&D intensity indicator, we construct the corresponding expression such that $[w_0^N L_{r0}^N/(w_0^N L_{r0}^N + c_0^N L_0^N)]/[w_0^S L_{r0}^S/(w_0^S L_{r0}^S + c_0^S L_0^S)] = 2.117$.[29] Together with equations (46), (47) and (54), $\{\kappa, \gamma/\beta\}$ and the equilibrium values of $\{\Phi, \lambda^S\}$ are simultaneously solved. Given the calibrated value of κ, equation (41) pins down the externality of intertemporal knowledge spillover ξ, and the definition of $\kappa = z^{\sigma-1}$ determines the value of quality step size z. All above calibrated values are reported in Table 1.

Table 1: Calibrated parameter values

ρ	σ	α	μ^N	μ^S	δ	κ	γ/β	z	ξ
0.05	2.9	0.829	1.3	1.25	0.0625	2.609	8.854	1.656	0.821

5.2 Benchmark estimation results

Given the benchmark calibrated parameter values, we now conduct the following experiments by enhancing patent protection in China and the US, respectively. We start off by exploring the situations in China. As reported in Table 2, we find that the average quality per Northern worker Φ increases by 0.577% (percent change) in response to a permanent 1% (percent change) rise in the level of patent breadth μ^S in China, implying a temporary higher rate of innovation λ^N in the North according to (40). Moreover, the international technology transfer rate λ^S increases correspondingly by 5.225% (percent change). When expressing the welfare changes as the usual equivalent variation in consumption, we find that a stricter patent policy in China leads to a welfare gain of 2.141% in China. From Lemma 2, we know that the change in c_0^S comes from the

[25] The data is included in International Compensations of Hourly Compensation Costs in Manufacturing, 2016 - China and India, Table 4.

[26] It is the value of $\beta\Phi$, which is independent of β, that affects equilibrium variables in the model. Therefore, we normalize β to unity for simplicity only when reporting the value of Φ.

[27] Studies in the literature have considered different values for the arrival rate of innovations. For instance, Caballero and Jaffe (2002) and Laitner and Stolyarov (2013) estimate the mean rate of creative destruction to be roughly 3.5%, while Lanjouw (1998) shows that the probability of obsolescence ranges from 7% to 12%. Thus, we consider an intermediate value of 5% within this range.

[28] The indicator for China is available during the period of 1991-2016. Both indicators for the US and China are available in https://data.oecd.org/rd/gross-domestic-spending-on-r-d.htm.

[29] The subscript of time 0 indicates that the economy is on the initial balanced-growth path before being intervened by changes in patent policy.

changes in w_0^S and I^S. The numerical results show that as μ^S rises by one percent, w_0^S increases by 2.396%, whereas c_0^S increases by 2.141%. This means that I^S decreases marginally by 0.255%, which implies a decline in the household's asset-wage income ratio. Finally, although the rise in μ^S narrows the wage gap ω by 0.900% (percent change), it still raises the wage rate in the US ω_0^N by 1.492%.[30] The increase in ω_0^N in turn causes a welfare gain of 1.546% in the US, but the size is smaller than that in China.

Table 2: Benchmark simulation

	Φ	λ^S	ω	$\Delta \ln \omega_0^N$	$\Delta \ln \omega_0^S$	$\Delta \ln c_0^N$	$\Delta \ln c_0^S$
	2.940	0.0194	20.101	-	-	-	-
$\Delta\mu^S$	2.957	0.0204	19.920	1.492%	2.396%	1.546%	2.141%
$\Delta\mu^N$	3.034	0.0186	20.225	8.488%	7.873%	8.792%	9.431%

Furthermore, Table 2 displays that a permanent 1% (percent change) increase in the level of patent breadth μ^N in US raises the average quality per Northern worker Φ by 3.218% (percent change), as the result of the Southern population size α being relatively small as shown in Proposition 3,[31] despite of a large number of population in China. In this case, the positive effect of a larger μ^N through price markup outweighs the negative effect via products manufacturing, raising the incentives for Northern innovation. Correspondingly, Φ rises permanently and the innovation rate λ^N in the North rises temporarily. In addition, the technology transfer rate λ^F from the US to China decreases by 3.993% (percent change); it is caused in part by a decrease in adaptive R&D because of a lower level of Southern R&D labor, and an reinforcing effect from the increase in Φ also makes the technology transfer more difficult. Moreover, the US-China wage gap ω enlarges by 0.617% (percent change), and the wage rates in both countries increase significantly (i.e., 8.488% in the US and 7.873% in China) in response to a larger μ^N. Accordingly, a strengthening of patent protection in the US yields a welfare gain of 8.792% in the US and 9.341% in China, respectively. In contrast to the changes caused by a larger μ^S in China, more welfare gains in the two countries are achieved by a stronger patent policy in the US, because of the substantial increases in the wage rates of both countries. Interestingly, in the above policy experiments, China benefits more than the US from a strengthening of patent protection in either country.

5.3 Robustness check

We now perform two robustness checks on our numerical exercise to illustrate how the quantitative results will vary under different assumptions. Specifically, we first consider alternative values of the innovation-arrival rate and then of the relative R&D intensity.

[30] According to International Labour Organization Global Wage Report 2018/19, the increase in the real average wages of emerging G20 economies (by triple) is more significant than the counterpart of advanced G20 economies (by 9%) during 1999-2017.

[31] According to (A.12), the threshold value $\bar{\alpha}$ in this numerical analysis is 0.996.

5.3.1 Innovation-arrival rate

Given the various estimates of the US innovation-arrival rate in the existing literature, such as Lanjouw (1998) and Caballero and Jaffe (2002), in this subsection we consider two alternative values of the innovation-arrival rate $\lambda^N \in \{0.1, 0.15\}$. Having other parameter values remain unchanged as in the benchmark, we perform the same policy experiment by raising μ^S and μ^N by 1%, respectively. Based on the numerical results as displayed in Table 3, it can be seen that a higher long-run innovation arrival rate λ^N tends to mitigate the effects of both the Southern patent instrument μ^S and the Northern patent instrument μ^N on all economic variables, except the relative wage. For example, in the case of $\lambda^N = 0.1$, raising the degree of IPR in China causes a smaller increase in the average quality per US worker Φ (i.e., 0.544%) and the rate of international technology transfer λ^F (i.e., 5.095%), as compared to the benchmark case (i.e., 0.577% and 5.225%, respectively). Similar patterns of the results are found when raising the degree of IPR in the US, that is, a rise of 3.072% in the average quality per US worker Φ and a decline of 3.834% in the international technology transfer rate λ^F, as compared to 3.218% and 3.993%, respectively, in the benchmark. As for the welfare effects, a strengthened IPR protection in either country leads to less welfare gains in contrast to the benchmark. However, despite of these small changes in the magnitudes of each economic variable, the overall pattern of the cross-country effects of IPR policy is consistent with the benchmark case. In other words, strengthening IPR in one country yields larger welfare improvements in China than in the US.

Table 3: Simulation under $\lambda^N \in \{0.1, 0.15\}$

	$\Delta\Phi$	$\Delta\lambda^S$	$\Delta\omega$	$\Delta \ln \omega_0^N$	$\Delta \ln \omega_0^S$	$\Delta \ln c_0^N$	$\Delta \ln c_0^S$
$\lambda^N = 0.1$							
$\Delta\mu^S$	0.544%	5.095%	-0.899%	1.389%	2.293%	1.423%	2.101%
$\Delta\mu^N$	3.072%	-3.834%	0.617%	8.079%	7.364%	8.271%	8.497%
$\lambda^N = 0.15$							
$\Delta\mu^S$	0.529%	5.032%	-0.899%	1.341%	2.245%	1.365%	2.091%
$\Delta\mu^N$	3.000%	-3.759%	0.617%	7.889%	7.274%	8.029%	8.072%

5.3.2 R&D intensity

To conduct this robustness check, we consider two scenarios. First, as argued in Comin (2004) and Jones (2016), the data on R&D expenditure reported by US firms are likely to underestimate the resources devoted into innovation-related activities.[32] Thus, we use the data from the most recent Science and Engineering Indicators 2018,[33] to consider a higher measure for the US R&D intensity in 2015 at the value of 3.9%. With the R&D intensity in China unchanged, we reexamine the quantitative results under a larger US-China relative R&D intensity, which is 3.181 now. Then, preserving the other parameter values as in the benchmark, we report in Table 4 the re-calibrated values and the new quantitative results.[34] Given that the relative productivity of the

[32]See Jones (2016) for a detailed discussion.

[33]See details in https://www.nsf.gov/statistics/2018/nsb20181/report, Table 4-10.

[34]The value of δ is adjusted to ensure that both Assumptions 1 and 2 hold.

Southern manufacturing labor to the Northern one becomes lower (i.e., a lower δ) and the relative productivity of adaptive R&D to innovative R&D becomes higher (i.e., a lower γ/β), increasing Southern patent breadth μ^S by 1% yields a larger increase in the average quality per US worker Φ (i.e., 0.701% versus 0.577% in the benchmark) and in international technology transfer λ^F (i.e., 5.531% versus 5.225% in the benchmark). In contrast, increasing Northern patent breadth μ^N by 1% leads to a smaller increase in Φ (i.e., 3.126% versus 3.218% in the benchmark) and a larger decrease in λ^F (i.e., -4.082% versus -3.993% in the benchmark). As compared to the benchmark case, a smaller size in the wage increase and the welfare gain is observed when enhancing IPR in both countries. Nevertheless, again, the overall pattern of the cross-country effects of IPR policy still holds as in the benchmark estimation.

Table 4: Simulation under a larger relative R&D intensity.

δ	κ	γ/β	z	ξ	Φ	λ^S	ω
0.0585	2.298	5.434	1.549	0.778	2.998	0.0202	20.101

	$\Delta\Phi$	$\Delta\lambda^S$	$\Delta\omega$	$\Delta\ln\omega_0^N$	$\Delta\ln\omega_0^S$	$\Delta\ln c_0^N$	$\Delta\ln c_0^S$
$\Delta\mu^S$	0.701%	5.531%	-0.940%	1.416%	2.320%	1.483%	2.051%
$\Delta\mu^N$	3.126%	-4.082%	0.644%	6.515%	4.496%	6.816%	7.247%

Second, when considering the fact that the R&D expenditure share of GDP in China has increased sharply from 0.639% in 1997 to 2.108% in 2016 whereas the US counterpart remains roughly constant according to OECD data, it is reasonable to redo the numerical exercise under a lower US-China relative R&D intensity. Thus, we consider an alternative case by using the data for the period 1997-2016 during which the relative R&D intensity between the US and China is 1.886. The re-calibrated parameters and equilibrium variables under this value of relative R&D intensity are reported in Table 5.[35] Differing from the case under a larger relative R&D intensity, a higher value of δ and of γ/β causes a tightening of Southern patent protection μ^S by 1% to yield a smaller increase in the average quality per US worker Φ (i.e., 0.526% versus 0.577% in the benchmark) and in the international technology transfer rate λ^F (i.e., 5.090% versus 5.225% in the benchmark). Additionally, this set of parameter values causes a tightening of Northern patent policy μ^N by 1% to yield a larger increase in Φ (i.e., 3.256% versus 3.218% in the benchmark) and a smaller decrease in λ^F (i.e., -3.959% versus -3.993% in the benchmark). Finally, although the welfare effects of strengthening IPR protection in this case become larger, China continues to benefit more than the US from the policy change in either country.

6 Conclusion

In this study, we analyze the cross-country effects of IPR protection on innovation and technology transfer in an open-economy Schumpeterian growth model with North-South product cycles. The IPR regime takes patent breadth as the policy instrument in both countries to capture the impacts of market power on the R&D incentives of Northern and Southern firms. We find that broadening patent breadth in the South leads to a permanent decrease in the North-South

[35] Again, the value of δ is adjusted to guarantee that both Assumptions 1 and 2 hold.

Table 5: Simulation under a smaller relative R&D intensity.

δ	κ	γ/β	z	ξ	Φ	λ^S	ω
0.0644	2.685	10.639	1.682	0.829	2.916	0.0185	20.101

	$\Delta\Phi$	$\Delta\lambda^S$	$\Delta\omega$	$\Delta \ln \omega_0^N$	$\Delta \ln \omega_0^S$	$\Delta \ln c_0^N$	$\Delta \ln c_0^S$
$\Delta\mu^S$	0.526%	5.090%	-0.886%	1.437%	2.327%	1.487%	2.082%
$\Delta\mu^N$	3.256%	-3.959%	0.607%	9.024%	8.419%	9.330%	9.934%

wage gap, a temporary increase in the Northern innovation rate, and a permanent increase in technology transfer. Nevertheless, broadening patent breadth in the North leads to a permanent increase in the North-South wage gap, ambiguous effects on the Northern innovation rate, and a permanent decrease in technology transfer. In particular, the size of Southern population plays a critical role in disambiguating the effect of Northern patent protection on innovation. By calibrating the model to the China-US data, our numerical analysis shows that the effect of tightening patent protection in either country is significantly welfare-improving, but the policy change in the US generates larger effects on the global economy than that in China. Furthermore, China receives more welfare gains than the US when IPR protection in one country is strengthened. Therefore, this study presents an example in the welfare analysis that sheds some light on the justification for (both developed and developing) countries to make the upgrading of their IPR, following the agreement on TRIPS.

There are two potential dimensions to extend the present paper. First, the current model is based on an open-economy version of the quality-ladder model to explore the effects of patent breadth on innovation and international technology transfer. To characterize the important properties of the innovation structure, these effects could be reexamined in an open-economy version of the variety-expanding model as in Gustafsson and Segerstrom (2011). Moreover, the effects of patent breadth could be investigated in a framework with different modes of international technology transfer that abstract from FDI, such as licensing in Yang and Maskus (2001) and Tanaka *et al.* (2007) and imitation in Gustafsson and Segerstrom (2010) and Lorenczik and Newiak (2012). These crucial issues can represent interesting directions for future research.

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Appendix A

A.1 Proof of Lemma 1

We follow Dinopoulos and Segerstrom (2010) to provide the proof. The dynamics of the quality index for Q_t^N and Q_t^S are given by respectively

$$\begin{aligned}\dot{Q}_t^N &= \int_{\theta^N}\left[\kappa^{n_t(j)+1}-\kappa^{n_t(j)}\right]\lambda_t^N dj+\int_{\theta^S}\kappa^{n_t(j)+1}\lambda_t^N dj-\int_{\theta^N}\kappa^{n_t(j)}\lambda_t^S dj \\ &= (\kappa-1)\lambda_t^N Q_t^N+\kappa\lambda_t^N Q_t^S-\lambda_t^S Q_t^S,\end{aligned} \tag{A.1}$$

and

$$\dot{Q}_t^S = \int_{\theta^N}\kappa^{n_t(j)}\lambda_t^S dj-\int_{\theta^S}\kappa^{n_t(j)}\lambda_t^N dj=\lambda_t^S Q_t^N-\lambda_t^N Q_t^S. \tag{A.2}$$

Since the industry composition is stationary over time in the steady state, the growth rate of average quality in the North and the counterpart in the South must be equal to each other and they are constant over time. Therefore,

$$\frac{\dot{Q}_t^N}{Q_t^N}=\frac{\dot{Q}_t^S}{Q_t^S}. \tag{A.3}$$

Substituting (A.1) and (A.2) into (A.3), together with $Q_t = Q_t^N + Q_t^S$, yields (29) and (30).

A.2 Proof of Lemma 2

Following Dinopoulos and Segerstrom (2010), we assume that the Northern household finances innovative R&D in equilibrium such that $L_t^N a_t^N = \int_0^1 v_t^N(j)dj = \beta w_t^N \int_0^1 q_t(j)dj = \beta w_t^N Q_t^{1-\xi}$, where the second equality is obtained by using (18). Hence, we have

$$a_t^N = \beta w_t^N Q_t^{1-\xi}/L_t^N = \beta w_t^N \Phi. \tag{A.4}$$

Using (49) and (A.4), we can derive c_0^N as shown in Lemma 2.

Moreover, the assumption that adaptive R&D is financed by the Southern household in equilibrium implies $a_t^S = v_t^S/L_t^S$ and

$$\begin{aligned}v_t^S &= \int_{\theta^N} v_t^S(j)dj=\int_{\theta^N}\left[\gamma w_t^S q_t(j)Q_t^{-\xi}+v_t^N(j)\right]dj \\ &= \gamma w_t^S Q_t^{-\xi}\int_{\theta^N}q_t(j)dj+\beta w_t^N Q_t^{-\xi}\int_{\theta^N}q_t(j)dj=\left(\gamma w_t^S+\beta w_t^N\right)Q_t^{-\xi}Q_t^N,\end{aligned} \tag{A.5}$$

where the third equality uses (18) and the last equality uses the definition of Q_t^N in (28). Thus, we obtain

$$a_t^S=\left(\gamma w_t^S+\beta w_t^N\right)\frac{Q_t^N}{Q_t}\frac{Q_t^{1-\xi}}{L_t^N}\frac{L_t^N}{L_t^S}=\left(\gamma w_t^S+\beta w_t^N\right)\frac{\kappa\lambda^N\Phi(1-\alpha)}{\alpha(\kappa\lambda^N+\lambda^S)}, \tag{A.6}$$

where Q_t^N/Q_t stems from Lemma 1. Using the relation $c_t^S = w_t^S + (\rho - g_L)a_t^S$, we obtain c_0^S as shown in Lemma 2.

Finally, the expression of w_0^S is obtained by substituting (9) and (10) into the aggregate price index such that

$$
\begin{aligned}
&\left\{\int_0^1 [p_t(j)]^{1-\sigma} dj\right\}^{\frac{1}{1-\sigma}} = 1 \\
\Leftrightarrow &\left\{\int_{\theta^N} \left[\frac{\mu^N w_t^N}{z^{n_t(j)}}\right]^{1-\sigma} dj + \int_{\theta^S} \left[\frac{\mu^S w_t^S}{\delta z^{n_t(j)}}\right]^{1-\sigma} dj\right\}^{\frac{1}{1-\sigma}} = 1 \\
\Leftrightarrow &w_t^S \left\{\left(\mu^N \omega\right)^{1-\sigma} Q_t^N + \left(\mu^S/\delta\right)^{1-\sigma} Q_t^S\right\}^{\frac{1}{1-\sigma}} = 1 \\
\Leftrightarrow &w_t^S = Q_t^{\frac{1}{\sigma-1}} \left\{\left(\mu^N \omega\right)^{1-\sigma} \frac{\kappa\lambda^N}{\kappa\lambda^N + \lambda^S} + \left(\mu^S/\delta\right)^{1-\sigma} \frac{\lambda^S}{\kappa\lambda^N + \lambda^S}\right\}^{\frac{1}{\sigma-1}},
\end{aligned}
\tag{A.7}
$$

where we have used the definitions of Q_t^N and Q_t^S in (28), and Q_t^N/Q_t and Q_t^S/Q_t from Lemma 1. Then, using $Q_0 = (\Phi L_0^N)^{1/(1-\xi)}$ yields w_0^S as shown in Lemma 2.

A.3 Proof of Proposition 1

First, we examine the effect of μ^S on ω. Define the RHS of (54) as

$$f(\mu^N, \mu^S) \equiv \delta^{\sigma-1} \left(\frac{\mu^N}{\mu^S}\right)^{\sigma} \frac{\mu^S - 1}{\mu^N - 1}.$$

Differentiating $f(\mu^N, \mu^S)$ with respect to μ^S yields

$$\frac{\partial f(\mu^S, \mu^N)}{\partial \mu^S} > 0 \Leftrightarrow \underbrace{\delta^{\sigma-1} \frac{(\mu^N)^{\sigma}}{(\mu^N - 1)(\mu^S)^{\sigma+1}}}_{>0} \left[\mu^S - \sigma(\mu^S - 1)\right] > 0, \tag{A.8}$$

because $\mu^S < \sigma/(\sigma - 1)$. Given the LHS of (54) is a decreasing function of ω, an increase in μ^S that raises $f(\mu^N, \mu^S)$ leads to a lower ω.

Next, we examine the effect of μ^N on ω. Similarly, differentiating $f(\mu^N, \mu^S)$ with respect to μ^N yields

$$\frac{\partial f(\mu^S, \mu^N)}{\partial \mu^N} < 0 \Leftrightarrow \underbrace{\delta^{\sigma-1} \frac{(\mu^S - 1)(\mu^N)^{\sigma-1}}{(\mu^S)^{\sigma}}}_{>0} \frac{\left[\sigma(\mu^N - 1) - \mu^N\right]}{(\mu^N - 1)^2} < 0, \tag{A.9}$$

because $\mu^N < \sigma/(\sigma - 1)$. Again, considering that the LHS of (54) is a decreasing function of ω, a decrease in μ^N that reduces $f(\mu^N, \mu^S)$ leads to a higher ω.

A.4 Proof of Proposition 2

Given the result in Proposition 1 such that $\omega(\mu^N, \mu^S)$ is decreasing in μ^S, it is easy to show graphically, according to Figure 1, that a rise in μ^S shifts the Southern steady-state R&D curve (47) to the right, whereas it has no impact on the Northern steady-state R&D curve (46). Thus, both Φ and λ^S increase in response. According to (40), a permanent higher Φ must be associated with a temporary increase in the innovation rate λ^N above its steady-state level $\lambda^N = g_L/(\sigma-1)$. This completes the proof for Proposition 2.

A.5 Proof of Proposition 3

First, according to (46) and (47), we can show graphically in Figure 1 that an increase in μ^N shifts the North curve to the left and the South curve to the right, leading to an unambiguously negative effect on λ^S. This completes the proof for (ii).

As for (i), rewriting λ^S from (46) to

$$\lambda^S = \frac{\beta\kappa\lambda^N\Phi(\rho+\lambda^N)}{(\mu^N-1)(1-\beta\lambda^N\Phi)} - \kappa\lambda^N, \tag{A.10}$$

and substituting it into (47) to solve for Φ yields

$$\Phi = \frac{1}{\rho+\lambda^N\mu^N}\left[\frac{\alpha(\rho+\lambda^N)}{(1-\alpha)\chi_1} + \frac{\mu^N-1}{\beta}\right], \tag{A.11}$$

where

$$\chi_1 = \frac{(\rho+\lambda^N)(\gamma+\beta\omega)}{\mu^S-1} + \gamma\kappa\lambda^N.$$

Differentiating Φ with respect to μ^N yields

$$\begin{aligned}
&\frac{\partial\Phi}{\partial\mu^N} \gtrless 0\\
\Leftrightarrow &\frac{-\lambda^N}{(\rho+\lambda^N\mu^N)^2}\left\{\frac{\alpha(\rho+\lambda^N)}{(1-\alpha)\chi_1} + \frac{\mu^N-1}{\beta}\right\} + \frac{1}{\rho+\lambda^N\mu^N}\left\{-\frac{\alpha(\rho+\lambda^N)}{(1-\alpha)\chi_1^2}\frac{\beta(\rho+\lambda^N)}{\mu^S-1}\frac{\partial\omega}{\partial\mu^N} + \frac{1}{\beta}\right\} \gtrless 0\\
\Leftrightarrow &-\lambda^N\left\{\frac{\alpha(\rho+\lambda^N)}{(1-\alpha)\chi_1} + \frac{\mu^N-1}{\beta}\right\} + (\rho+\lambda^N\mu^N)\left\{\frac{1}{\beta} - \frac{\alpha(\rho+\lambda^N)}{(1-\alpha)\chi_1^2}\frac{\beta(\rho+\lambda^N)}{\mu^S-1}\frac{\partial\omega}{\partial\mu^N}\right\} \gtrless 0\\
\Leftrightarrow &-\frac{\alpha\lambda^N}{(1-\alpha)\chi_1} + \frac{1}{\beta} - \frac{\alpha\beta(\rho+\lambda^N)(\rho+\lambda^N\mu^N)}{(1-\alpha)(\mu^S-1)\chi_1^2}\frac{\partial\omega}{\partial\mu^N} \gtrless 0\\
\Leftrightarrow &\frac{1-\alpha}{\alpha} \gtrless \frac{\beta^2(\rho+\lambda^N)(\rho+\lambda^N\mu^N)}{(\mu^S-1)\chi_1^2}\frac{\partial\omega}{\partial\mu^N} + \frac{\beta\lambda^N}{\chi_1},
\end{aligned} \tag{A.12}$$

where we have divided both sides of the third inequality to obtain the fourth inequality. Denote by $\overline{\alpha}$ the expression in the RHS of the last inequality. Thus, when $\alpha < \overline{\alpha}$ (namely α is sufficiently small), a rise in μ^N increases Φ permanently, leading to a temporary higher rate of innovation λ^N according to (40); otherwise, when $\alpha > \overline{\alpha}$ (namely α is sufficiently large), a rise in μ^N decreases Φ permanently, leading to a temporary lower rate of λ^N. This completes the proof for (i).

A.6 Calibration strategy

Given σ, δ, μ^N, and μ^S, we obtain γ/β by using (54):

$$\frac{\gamma}{\beta\omega^\sigma} + \omega^{1-\sigma} = \delta^{\sigma-1}\left(\frac{\mu^N}{\mu^S}\right)^\sigma \frac{\mu^S - 1}{\mu^N - 1} \tag{A.13}$$

Given γ/β, we build up three equations to solve the three unknowns, which are κ, λ^S and Φ. The three equations are

- US-China relative R&D intensity:

$$\begin{aligned} 2.117 &= \frac{w_0^N L_{r0}^N}{w_0^N L_{r0}^N + c_0^N L_0^N} \frac{w_0^N L_{r0}^N + c_0^N L_0^N}{w_0^N L_{r0}^N} \\ &= \frac{\beta\Phi\lambda^N}{\beta\Phi(\rho - g_L + \lambda^N) + 1} \cdot \frac{\frac{\gamma}{\beta}\lambda^S + (\rho - g_L)(\frac{\gamma}{\beta} + \omega) + \frac{\alpha(\kappa\lambda^N + \lambda^S)}{\kappa\lambda^N\beta\Phi(1-\alpha)}}{\frac{\gamma}{\beta}\lambda^S}, \end{aligned} \tag{A.14}$$

  where we have used (50), (51), $L_{r0}^N = \beta\lambda^N Q_0^{1-\xi}$ from (33), and $L_{r0}^S = \gamma\lambda^S Q_0^{1-\xi}(Q_0^N/Q_0)$ from (37) in sequence.

- The Northern-steady-state condition in (46):

$$\lambda^S = \frac{\beta\kappa\lambda^N\Phi(\rho + \lambda^N)}{(\mu^N - 1)(1 - \beta\lambda^N\Phi)} - \kappa\lambda^N. \tag{A.15}$$

- The Southern-steady-state condition in (47):

$$1 = \frac{\Phi\lambda^S(1-\alpha)}{\alpha(\kappa\lambda^N + \lambda^S)}\left\{\frac{(\rho + \lambda^N)(\gamma + \beta\omega)}{\mu^S - 1} + \gamma\kappa\lambda^N\right\} \tag{A.16}$$

Appendix B

B.1 Alternative specification on R&D

To examine the robustness of our results in the baseline model, in this section we consider an alternative R&D specification that features fully endogenous growth in the long run. The main difference in this version of model is the instantaneous probability of innovative and adaptive R&D. Specifically, if an R&D entrepreneur employs an amount of Northern labor $L^N_{r,t}(j)$ to perform innovative R&D in industry j, then she succeeds in inventing the next higher quality product in this industry with an instantaneous probability given by

$$\lambda^N_t(j) = \frac{L^N_{r,t}(j)}{\beta L^N_t}. \tag{B.1}$$

If the Southern affiliate of a Northern leader in industry j employs an amount of Southern labor $L^S_{r,t}(j)$ to conduct adaptive R&D, then the Northern firm succeeds in shifting the production to the Southern affiliate with an instantaneous probability given by

$$\lambda^S_t(j) = \frac{L^S_{r,t}(j)}{\gamma L^S_t}. \tag{B.2}$$

The corresponding zero-expected profit conditions for innovative R&D and adaptive R&D are respectively,

$$v^N_t(j) = \beta w^N_t L^N_t, \tag{B.3}$$

and

$$v^S_t(j) - v^N_t(j) = \gamma w^S_t L^S_t. \tag{B.4}$$

In this setup, we now derive the Northern and Southern steady-state conditions and the steady-state relative wage condition. Using (B.1), the total amount of labor employed for innovative R&D is given by

$$L^N_{r,t} = \int_0^1 L^N_{r,t}(j)dj = \beta L^N_t \lambda^N, \tag{B.5}$$

Thus, the Northern labor market clearing condition (in per capita term) in (34) now becomes

$$1 = \frac{\kappa\lambda^N}{\kappa\lambda^N + \lambda^S}\frac{\bar{L}^N_{x,t}}{L^N_t} + \beta\lambda^N. \tag{B.6}$$

Similarly, using (B.2), we show that the amount of labor employed in adaptive R&D is given by

$$L^S_{r,t} = \int_{\theta^N} L^S_{r,t}(j)dj = \gamma L^S_t \lambda^S \left(\frac{\lambda^N}{\lambda^N + \lambda^S}\right), \tag{B.7}$$

where (25) is applied. The Southern labor market clearing condition then becomes

$$1 = \frac{\lambda^S}{\kappa\lambda^N + \lambda^S}\frac{\bar{L}^F_{x,t}}{L^S_t} + \gamma\lambda^S \left(\frac{\lambda^N}{\lambda^N + \lambda^S}\right). \tag{B.8}$$

Substituting (15) and (42) into (B.3) and making use of symmetry yield the steady-state innovative R&D condition such that

$$\left(\mu^N - 1\right) \frac{\bar{L}^N_{x,t}}{L^N_t} = \beta(\rho + \lambda^N). \tag{B.9}$$

Substituting (15), (16), (42), and (43) into (B.4) gives rise to the following steady-state adaptive R&D condition:

$$\left(\mu^S - 1\right) \frac{\bar{L}^F_{x,t}}{L^S_t} - \left(\mu^N - 1\right) \frac{\bar{L}^N_{x,t}}{L^S_t} = \gamma\left(\rho + \lambda^N\right). \tag{B.10}$$

Combining (B.6) with (B.9) yields the Northern steady-state condition given by

$$1 = \beta\lambda^N \left[\frac{\kappa(\rho + \lambda^N)}{(\kappa\lambda^N + \lambda^S)(\mu^N - 1)} + 1\right]. \tag{B.11}$$

Combining (B.8) with (B.10) yields the Southern steady-state condition given by

$$1 = \lambda^S \left\{\frac{(\rho + \lambda^N)[\gamma + \beta\omega(1-\alpha)/\alpha]}{(\mu^S - 1)(\kappa\lambda^N + \lambda^S)} + \frac{\gamma\lambda^N}{\lambda^N + \lambda^S}\right\}, \tag{B.12}$$

where we have applied $L^N_t / L^S_t = (1-\alpha)/\alpha$. Using (B.9), (B.10) and (53), we can show the steady-state wage condition as follows:

$$\frac{\gamma}{\beta\omega^\sigma} + \frac{(1-\alpha)\omega^{1-\sigma}}{\alpha} = \delta^{\sigma-1}\left(\frac{\mu^N}{\mu^S}\right)^\sigma \frac{(\mu^S-1)(1-\alpha)}{\alpha(\mu^N-1)}, \tag{B.13}$$

which is an implicit function that determines the steady-state equilibrium value of the relative wage $\omega(\mu^N, \mu^S)$. (B.13) also implies that ω is increasing in μ^N whereas it is decreasing in μ^S, which yields the same results as in Proposition 1 under the semi-endogenous setting.[36]

Next, we derive the steady-state rate of economic growth. Equation (12) shows that the labor demand for an average-quality product produced by a Northern leader is $\bar{L}^N_{x,t} = Q_t Y_t \left(\mu^N w^N_t\right)^{-\sigma}$. Equation (39) implies that the growth rate of quality index is $\dot{Q}_t/Q_t = (\kappa - 1)\lambda^N_t$. It can be shown that $\dot{Y}_t/Y_t = \dot{C}_t/C_t = \dot{c}^N_t/c^N_t + g_L$ by using (5) and $\dot{c}^N_t/c^N_t = \dot{w}^N_t/w^N_t = g$ by using (2). Combining these conditions yields $g = (\kappa-1)\lambda^N/(\sigma-1)$, where the Northern innovation-arrival rate λ^N is implicitly determined by (B.11) - (B.13).

As for social welfare, the steady-state welfare function of the Northern household is the same as (48). By analogous derivations in Lemma 2, we can show that

$$a^N_0 = \frac{v^N_0}{L^N_0} = \beta w^N_0, \tag{B.14}$$

$$a^S_0 = \frac{v^S_0}{L^S_0} = \frac{1}{L^S_0}\int_{\theta^N}\left[v^N_0(j) + \gamma w^S_0 L^S_0\right] dj = \theta^N w^S_0 \left[\frac{\beta(1-\alpha)\omega}{\alpha} + \gamma\right]. \tag{B.15}$$

Thus, the balanced-growth level of consumption per capita for both countries now are, respec-

[36]Following the proof in the Appendix A.3, it is easy to show the same results for the effects of patent breadth on the relative wage by differentiating (B.13) with respect to μ^N and μ^S.

tively,

$$c_0^N = w_0^N \left[1 + \beta(\rho - g_L)\right] = \omega w_0^S \left[1 + \beta(\rho - g_L)\right], \tag{B.16}$$

and

$$c_0^S = w_0^S \left\{1 + \theta^N(\rho - g_L)\left[\frac{\beta(1-\alpha)\omega}{\alpha} + \gamma\right]\right\}, \tag{B.17}$$

where θ^N is given by (25) and w_0^S, which is similarly derived as (52), is given by

$$w_0^S = Q_0^{\frac{1}{\sigma-1}}\left[\left(\mu^N\omega\right)^{1-\sigma}\left(\frac{\kappa\lambda^N}{\kappa\lambda^N + \lambda^S}\right) + \left(\mu^S/\delta\right)^{1-\sigma}\left(\frac{\lambda^S}{\kappa\lambda^N + \lambda^S}\right)\right]^{\frac{1}{\sigma-1}}. \tag{B.18}$$

where initial Q_0 is normalized to unity.

Given its complexity, this extended model is hereafter solved numerically. The benchmark parameter values are given by the same set of values in the main text: $\{\rho, \sigma, \alpha, \mu^N, \mu^S, \kappa, z\} = \{0.05, 2.9, 0.829, 1.3, 1.25, 2.609, 1.656\}$. For the remaining parameters $\{\delta, \gamma, \beta\}$, we set δ to 0.0516 to ensure that Assumptions 1 and 2 hold, and calibrate β and γ by using equations (B.11), (B.12) and (B.13), with the following moments: the innovation arrival rate (i.e., 12%), the population growth rate (i.e., 0.5%)[37] and the relative wage between China and the US (i.e., 20.101). The calibrated parameter values are reported in Table 6. Given these parameter values, the equilibrium value of λ^S is 6.285%.

Table 6: Calibrated parameter values in the fully endogenous growth model

ρ	σ	α	μ^N	μ^S	δ	κ	σ	β	γ
0.05	2.9	0.829	1.3	1.25	0.0516	2.609	1.656	2.1190	0.0074

Given these calibrated parameter values, we consider the same experiments as in the baseline model by raising the level of patent breadth in China and the US (i.e., μ^S and μ^N) by 1% (percent change), respectively. The results are reported in Table 7. We find that a permanent increase in patent breadth μ^S in China decreases the wage gap ω by 1.043% (percent change), and increases the innovation arrival rate λ^N by 1.446% (percent change), the international technology transfer rate λ^S by 7.638% (percent change), and the growth rate of consumption g by 0.147% (percentage point). These changes are similar to those in the semi-endogenous growth model except that the Northern wage rate is depressed slightly by 0.330%. Moreover, the effects of a rise in μ^S on both Southern and Northern social welfare are similar to the counterparts in the semi-endogenous growth model; a 1% increase in μ^S leads to a welfare gain (in terms of equivalent variation in consumption) of 3.347% in China and 2.935% in the US, respectively. Therefore, strengthening patent protection in China in the fully endogenous growth model also benefits both countries in terms of welfare, and the benefit to China continues to be more significant than to the US.

Finally, as in the semi-endogenous growth model, the effects of strengthening patent protection in the US still lead to similar results on the innovation rate, the rate of international technology transfer and the relative wage in the fully endogenous growth model. Specifically,

[37]According to http://wdi.worldbank.org/tables, Table 2.2, Labor Force Structure, the growth rate of labor force in the US during 2007-2016 is 0.5%.

Table 7: Simulation under the alternative model

	$\Delta\lambda^N$	$\Delta\lambda^S$	$\Delta\omega$	Δg	$\Delta \ln \omega_0^N$	$\Delta \ln \omega_0^S$	$\Delta \ln U_0^N$	$\Delta \ln U_0^S$
$\Delta\mu^S$	1.446%	7.638%	-1.043%	0.147%	-0.330%	0.718%	2.935%	3.347%
$\Delta\mu^N$	4.944%	-0.130%	0.716%	0.502%	-0.736%	-1.450%	10.429%	10.213%

a permanent rise of 1% in patent breadth μ^N in the US raises the relative wage ω by 0.716% (percent change), the innovation arrival rate λ^N by 4.944% (percent change), and the growth rate of consumption g by 0.502% (percentage point), but it stifles the international technology transfer rate λ^S by 0.130% (percent change). In addition, the rise in μ^N leads to a welfare gain of 10.429% and 10.213% in the US and China, respectively. Analogous to the welfare effects of strengthening patent protection in China, strengthening patent protection in the US benefits both countries in terms of welfare. However, the benefit to China becomes less significant than to the US in this case.