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Hicks theorem: Effects of technological improvement in the Ricardian model ☆

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ABSTRACT

Using the Ricardian model, we formally prove Hicks' [Hicks, John (1953), "An Inaugural Lecture," Oxford Economic Papers 5(2), 117–135.] insight into the effects of technological improvement: uniform technological improvement at home benefits all countries (or at least does not hurt); export-biased technological improvement at home benefits the foreign country (or at least does not hurt), but import-biased technological improvement at home can hurt the foreign country as long as the comparative advantage is not reversed. We then study optimal strategies of technological improvement and show that for a small country it is optimal to choose export-biased technological improvement. For a large country, it is optimal to improve technology in both sectors at a rate proportional to the consumers' expenditure share. Therefore, if the expenditure share of the import sector is larger than that of the export sector, a large country will choose a relatively *import-biased* technological improvement, which will hurt its trading partner.

1. Introduction

There is a great deal of interest in the effects of technological improvement (through either innovation or technology transfer) in developing countries, such as China and India, on the welfare of developed countries, such as the United States. In his recent article, Samuelson (2004) argues that China could improve the technology in its import sector until its post-innovation relative labor productivity is identical to that in the United States, thus eliminating the U.S.'s comparative advantage, and any further gains from free trade. Samuelson's argument, however, is challenged by the "technology transfer paradox" discussed by Ruffin and Jones (in press) and Jones and Ruffin (2005). They show that the United States will actually gain from technological improvement in China's import sector if such technological improvement is sufficiently large to reverse comparative advantage. Samuelson's argument is also quite different from studies by Eaton and Kortum (2001, 2002, 2006) and by Alvarez and Lucas (2005), who argue that technological improvement in one country always benefits all other countries.

Hicks (1953) pointed out these varying effects of technological improvement more than half a century ago. In analyzing the effects of increasing productivity in the United States on Britain, Hicks pointed out that: 1) *uniform* technological improvement in one country benefits all countries, which is the case studied by Eaton and Kortum (2001, 2002, 2006) and Alvarez and Lucas (2005); 2) *export-biased* technological improvement benefits the foreign country, which is emphasized by Ruffin and Jones (in press) and Jones and Ruffin (2005); and 3) *import-biased* technological improvement hurts the foreign country, which is exactly Samuelson's argument. Hicks did not put his insight into a formal model. In this paper we will formally prove Hicks' insight with the Ricardian model.

Even in the simplest two-good, two-country Ricardian model, a formal analysis could be complicated since patterns (regimes) of trade are endogenous. "The problem with this model as a vehicle for discussing technical change is that too many things can

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happen"(Krugman, 1986, p. 153). However, we are able to pin down regime switches in a simple diagram by assuming that the utility function is Cobb–Douglas. The analysis then becomes straightforward.

The question that immediately emerges and that is crucial for economic development is: When will a country choose *export-biased*, and when will it choose *import-biased* technological improvement? Hicks (1953) proposed two stages of technological improvement: countries start with *export-biased* technological improvement in the first stage, and then move on to *import-biased* technological improvement in the second stage. We call this the Hicks path.

We study an optimal strategy of technological improvement in the Ricardian model, in order to shed some light on the Hicks path. We show that it is optimal for a small country to choose *export-biased* technological improvement, which benefits the partner country. A large country, however, finds it optimal to improve technology in both sectors. Interestingly, the optimal rate of technological improvement in each sector is proportional to the consumers' share of expenditure for that sector. Therefore, if the expenditure share of the import sector is larger than that of the export sector, the large country will choose a relatively *import-biased* technological improvement, which hurts its trade partner. When both countries are fully specialized, the home country may choose either an *export-biased* technological improvement, or a "catching-up" strategy, wherein it also improves the technology in its import sector and becomes self-sufficient in both goods. The catching-up strategy is shown to be optimal if the expenditure share on the importable good is sufficiently large, the country itself is large enough, and the technology gap with the advanced country in the import sector is relatively small.

This paper is related to the theoretical literature that investigates technology and trade. Besides the aforementioned works, Grossman and Helpman (1995) provide an excellent survey of the literature. Helpman (1993) analyzes the welfare effect of intellectual property rights policy and argues that faster diffusion will stimulate the research process in the innovating country. Demidova (2006) shows that technological improvement hurts the innovator's partner in the event that specialization does not occur.

The rest of the paper is organized as follows. Section 2 sets up the Ricardian model with three types of trade regimes and examines welfare effects of technological improvement. Section 3 studies the optimal strategy, and Section 4 concludes.

2. Welfare effects of technological improvement

Our analysis is based upon the standard Ricardian model, which has two goods and one factor (labor). We assume that only the home country improves its technology.

The goods market is perfectly competitive, and labor is perfectly mobile between industries in each country but immobile across countries. As usual, foreign variables are denoted by the superscript "*". Let $a_i(a_i*)$ be the amount of labor needed to produce a unit of good i (i=1, 2) in the home (foreign) country before the technological change. We assume that

$$a_1/a_2 < a_1^*/a_2^*. \quad (1)$$

Thus, the home country has a comparative advantage in producing good 1 before the technological change. The total labor force at home (abroad) is $L(L*)$. Let p^a (p^{a*}) denote the autarky price of good 1 relative to good 2 in the home (foreign) country. Perfect competition implies that $p^a = a_1/a_2$ and $p^{a*} = a_1^*/a_2^*$.

Now suppose that the home country and the foreign country open up to trade. Let p_i be the free trade price of each good, and $p = p_1/p_2$ be the relative price of good 1. Output in sector i is denoted by y_i. Let good 2 be the numeraire good, so that $p_2 = 1$. The world relative supply curve has a stepped shape, and is depicted in Fig. 1. The vertical and horizontal axes represent relative price p and relative supply of good 1, $y = (y_1 + y_1^*) / (y_2 + y_2^*)$, respectively. For the world relative price $p < p^a = a_1/a_2 < p^{a*} = a_1^*/a_2^*$, both

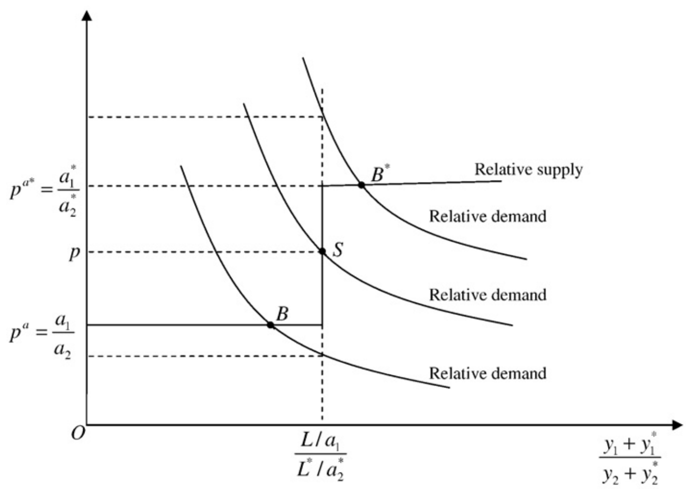

Fig. 1. The relative demand and the relative supply.

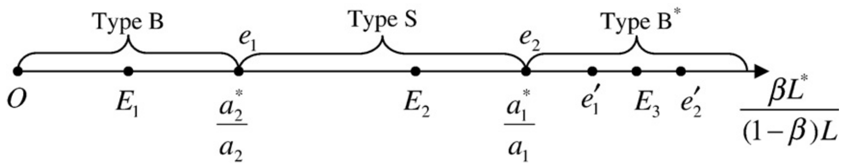

Fig. 2. The relative country size and the trade regime.

countries specialize in good 2, so the world relative supply of good 1 is zero. For $p^a<p<p^{a*}$, the home country specializes in good 1, while the foreign country specializes in good 2, and the world relative supply is $(L/a_1)/(L^*/a_2^*)$. Finally, if $p>p^{a*}>p^a$, both countries specialize in good 1, and the world relative supply of good 1 is infinity.

The utility function of the representative consumer in each country is the same, and is represented by

$$u(x_1,x_2)=x_1^{\beta}x_2^{1-\beta}. \tag{2}$$

Thus, the world relative demand is

$$x(p)=\frac{x_1}{x_2}=\frac{\beta}{(1-\beta)p} \Longleftrightarrow p(x)=\frac{\beta}{(1-\beta)x}. \tag{3}$$

The free trade outcome is determined by the relative demand curve, and the relative supply curve. There are three possibilities. The first possibility is that the relative demand curve cuts the lower horizontal segment of the relative supply curve at $p=a_1/a_2$, which is represented by equilibrium B in Fig. 1. This is referred to as regime B of trade in which the home country produces both goods, and exports good 1. The second possibility is that the demand curve cuts the vertical segment of the supply curve at $y=(y_1+y_1^*)\,/\,(y_2+y_2^*)$, which is represented by equilibrium S in Fig. 1. This is referred to as regime S of trade. Both countries are fully specialized in regime S. The third possibility is that the demand curve cuts the upper horizontal segment of the supply curve at $p=a_1^*/a_2^*$, which is represented by 1 2 equilibrium B* in Fig. 1. This is referred to as regime B* of trade, in which the foreign country produces both goods and exports good 2. It is easily seen that, in Fig. 1 at $x^s=(L/a_1)/(L^*/a_2^*)$, the inverse demand $p(x^s)=\frac{\beta a_1 L^*}{(1-\beta)a_2^* L}$ must be less than a_1/a_2 in regime B, greater than a_1/a_2 but less than a_1^*/a_2^* in regime S, and greater than a_1^*/a_2^* in regime B*.

Let $E=\frac{\beta L^*}{(1-\beta)L}$ be the relative size of the foreign country. As shown in Fig. 2, if $0\le E<\frac{a_2^*}{a_2}<\frac{a_1^*}{a_1}$, the home country is relatively large, and the two countries are engaged in regime B trade; if $\frac{a_2^*}{a_2}\le E<\frac{a_1^*}{a_1}$, the two countries are engaged in regime S trade, and if $E\ge\frac{a_1^*}{a_1}>\frac{a_2^*}{a_2}$, the foreign country is relatively large, and the two countries are engaged in regime B* trade. The countries' relative sizes and their productivity determine the trade regime.

2.1. Regime switch

Changes in technology change the relative productivity of the two countries and thus may switch the trade regime. With the Cobb–Douglas utility function, the regime switch is conveniently determined by the countries' relative sizes.

We analyze how the trade regime changes when the home country adopts *export-biased*, *import-biased*, or *uniform* technological improvements. In regime B, we have $E_B<\frac{a_2^*}{a_2}<\frac{a_1^*}{a_1}$. The home country is large, produces both goods, and exports good 1. *export-biased* technological improvement (which reduces a_1), *import-biased* technological improvement (which reduces a_2), and *uniform* technological improvement (which reduces a_1 and a_2 proportionally), all leave the inequality $E_B<\frac{a_2^*}{a_2}<\frac{a_1^*}{a_1}$ unchanged. Hence, technological improvement in regime B does not switch the trade regime.

In regime S, $\frac{a_2^*}{a_2}\le E_S<\frac{a_1^*}{a_1}$, and the home country is completely specialized in producing good 1. A reduction in a_1 (*export-biased* technological improvement) does not change the inequality, but a sufficiently large reduction in a_2 (*import-biased* technological improvement) can switch the trade regime from S to B. If proportional reductions in both a_1 and a_2 (*uniform* technological improvement) are sufficiently large, the trade regime can also switch from S to B.

Table 1
Regime switch

Starting point	Export-biased technological improvement	Import-biased technological improvement	Uniform technological improvement
Regime B* (Home country is small, specializes in good 1, exports good 1; Foreign country is large, produces both goods, exports good 2)	Sufficiently large reduction in a_1 can switch the regime from B* to S	Sufficiently large reduction in a_2 can reverse the comparative advantage and then switch the regime from B* to S	Sufficiently large proportional reductions in a_1 and a_2 can switch the regime from B* to S, and then S to B
Regime S (Home country specializes in good 1, exports good 1; Foreign country specializes in good 2, exports good 2)	No change	Sufficiently large reduction in a_2 can switch regime from S to B	Sufficiently large proportional reductions in a_1 and a_2 can switch regime from S to B
Regime B (Home country is large, produces both goods, exports good 1; Foreign country is small, specializes in good 2)	No change	No change	No change

In regime B*, wherein $E_{B^*} \geq \frac{a_1^*}{a_1} > \frac{a_2^*}{a_2}$, the home country is small and completely specializes in producing good 1, a sufficiently large *export-biased* technological improvement (reduction in a_1) can switch the trade regime from B* to S. A sufficiently large *import-biased* technological improvement (reduction in a_2), can first reverse the comparative advantage, and then switch the trade regime from B* to S. Finally, a sufficiently large *uniform* technological improvement (proportional reductions in a_1 and a_2) can switch the trade regime from B* to S. Further reductions in a_1 and a_2 can change the trade regime from S to B. We summarize the above results for regime switch in Table 1.

2.2. Welfare effects

We will first analyze the effects of *export-biased* technological improvement, then the effects of *import-biased* technological improvement, and lastly, the effects of *uniform* technological improvement. For each type of technological improvement, we start from regime B*, where $E \geq \frac{a_1^*}{a_1} > \frac{a_2^*}{a_2}$. The budget lines in the home country and the foreign country are

$$px_1 + x_2 = wL \tag{4}$$

$$px_1^* + x_2^* = w^* L^*. \tag{5}$$

Technological improvement changes the terms of trade, p, as well as real income, w/p and w^*/p. The former is denoted as the *terms of trade effect* and the later is denoted as the *real income effect*. In regime B*, the wage rates are $w = p/a_1$ and $w^* = 1/a_2^*$, and the free trade price is $p = a_1^*/a_2^*$. Consider an *export-biased* technological improvement that reduces a_1 to a_1'. Real income at home increases but the terms of trade are not affected; therefore, the home country budget line shifts out. This change, however, has no effect on the budget line abroad. Thus, under regime B*, the *export-biased* technological improvement increases welfare at home but has no effect on the foreign country.

Let the reduction in a_1 be sufficiently large so that the trade regime switches from B* to S $\left(a_1' < \frac{a_1^*(1-\beta)L}{\beta L^*}\right)$. When both countries are fully specialized, the world relative supply is $y = (L/a^1)/(L^*/a_2^*)$, as indicated by point S in Fig. 1. From the inverse demand function (3), the world relative price is now $p' = p(y) = \frac{\beta a_1' L^*}{(1-\beta) a_2^* L}$. The terms of trade at home, p, decline. The wage rates in the home country and in the foreign country are $w = p'/a_1' = \frac{\beta L^*}{(1-\beta) a_2^* L}$ and $w^* = 1/a_2^*$, respectively. As a_1 decreases, the real wage at home, $w/p = 1/a_1$, increases. Combining the real income effect and the terms of trade effect, the budget line shifts out as a_1 decreases. This implies that, in the home country, the *real income effect* dominates the *terms of trade effect*, and domestic welfare increases. The reduction in a_1 improves the terms of trade in the foreign country and swivels the foreign budget line out. Therefore, welfare in the foreign country increases as well.

Note that a decrease in a_1 in regime *S* never switches the trade regime from *S* to *B*. On the other hand, if we start from regime *B*, $p = a_1/a_2$, $w = p/a_1 = 1/a_2$ and $w^* = 1/a_2^*$. The decrease in a_1 swivels both the home and the foreign budget lines out, and therefore increases welfare at home and abroad.[2]

We now turn to *import-biased* technological improvement. Note that in regimes B* and S, the reduction in a_2 has no effect on the economy as long as the comparative advantage is not reversed. Once it does, one must have $\frac{a_1^*}{a_1'} < \frac{a_2^*}{a_2'}$. If so, a further reduction in a_2 becomes *export-biased* technological improvement; its welfare effect has been discussed above. In regime B, $p = a_1/a_2$, $w = p/a_1 = 1/a_2$, and $w^* = 1/a_2^*$. *import-biased* technological improvement increases both the wage rate and the terms of trade at home. The budget line shifts out and therefore improves welfare at home. However, the terms of trade in the foreign country, $1/p$, decline, while the foreign wage rate w^* is not affected by the reduction in a_2. The budget line for the foreign country shifts in, hence welfare in the foreign country decreases.

Uniform technological improvement is a combination of *export-biased* and *import-biased* technological improvements. From the above analysis we know that welfare in both countries either improves or does not change for all cases except the *import-biased* technological improvement in regime B when foreign welfare declines. When *uniform* technological improvement in regime B takes place, however, p is equal to a_1/a_2, which does not change since a_1 and a_2 decrease proportionally. This implies that welfare in the foreign country does not decline even in this worst case. Therefore, as expected, *uniform* technological improvement improves welfare in both home and foreign countries. We summarize the above cases of welfare effects in Table 2, and also state as the following Hicks theorem:

Theorem 1. (Hicks Theorem)

If the utility function is Cobb–Douglas, export-biased technological improvement at home benefits the home country, and either benefits the foreign country (or leaves its welfare unchanged). import-biased technological improvement at home benefits the home country, but can hurt the foreign country as long as the comparative advantage is not reversed. uniform technological improvement at home benefits all countries (or leaves welfare unchanged).

The above results were first stated by Hicks (1953) while analyzing the effect that increased U.S. productivity had on Britain. His main insight was that, given the terms of trade, the primary effect of technological progress is to increase the growing country's income and leave the foreign one unaffected, an effect we summarized as the real income effect. When the terms of trade are endogenous, there is a secondary effect, which we labeled the terms of trade effect. *Export-biased* technological progress lowers

[2] The above result relies on the assumption of the Cobb-Douglas utility function. If the demand is less elastic, as noted by both Samuelson (2004) and Ruffin and Jones (in press), immiserizing growth may occur.

Table 2
Welfare effects (assuming no reversal of comparative advantage and regime switch)

Starting point	Export-biased technological improvement	Import-biased technological improvement	Uniform technological improvement
Regime B* (Home country is small, specializes in good 1, exports good 1; Foreign country is large, produces both goods, exports good 2)	Home welfare improves Foreign welfare is unchanged	Home welfare is unchanged Foreign welfare is unchanged	Home welfare improves Foreign welfare is unchanged
Regime S (Home country specializes in good 1, exports good 1; Foreign country specializes in good 2, exports good 2)	Home welfare improves Foreign welfare improves	Home welfare is unchanged Foreign welfare is unchanged	Home welfare improves Foreign welfare is improves
Regime B (Home country is large, produces both goods, exports good 1; Foreign country is small, specializes in good 2, exports good 2)	Home welfare improves Foreign welfare improves	Home welfare improves Foreign welfare is worsen	Home welfare improves Foreign welfare is unchanged

the world price of the exported good at home, which hurts the home country but benefits its trading partner. The primary gain to the home country will dominate the secondary loss if demand is sufficiently elastic. The Cobb–Douglas case assumed in this paper is enough to guarantee that the gain is greater than the loss. *Import-biased* technological improvement changes the terms of trade in favor of the home country, so the home country may enjoy further gain, but the foreign country can be hurt.

Fifty years after Hicks, Samuelson (2004) again addresses the unpleasant effect of *import-biased* technological improvement on the foreign country. His argument, however, is challenged by the "technology transfer paradox" discussed by Ruffin and Jones (in press) and Jones and Ruffin (2005). They show that the United States will, nonetheless, gain from China's technological improvement in its import sector if such technological improvement is sufficiently large to reverse comparative advantage. Jones and Ruffin point out a complication to the formal analysis: trade regimes become endogenous when technology is changing. Our analysis shows that Hicks' insight still works, provided that the technological improvement is *import-biased* up to the point where comparative advantage is reversed.

3. Optimal strategy of technological improvement

The effects of *export-biased* versus *import-biased* technological improvements on welfare of the partner country are strikingly opposite. A crucial question that follows is when a country will choose the *export-biased* and when it will choose *import-biased* technological improvement. To answer this question, we investigate the optimal strategy of technological improvement in this section.

Departing from the assumption of costless technological improvement, we assume that the home country must allocate some labor to improve its technology. After the technological improvement the amount of labor needed to produce one unit of output in sector i is

$$a_1' = \frac{a_i}{1+\theta d_i}, \tag{6}$$

where $d_i>0$ is the amount of labor used in sector i for technological improvement. $\theta>0$ measures the efficiency of R&D in sector i, which is assumed, for simplicity, to be the same in both sectors. We start from a social planner's problem in which (d_1, d_2) is chosen to maximize the utility of the representative consumer. The social planner can pay $w(d_1+d_2)$ to the foreign country for a technology transfer, which is typically the case for developing countries, or she can spend $\frac{d_i}{L_i}$ share of labor per worker in sector i to improve working efficiency. Either way, the total income left for consumption after technological improvement at home is $w(L-d_1-d_2)$. It can be shown that the social planner's problem is equivalent to a decentralized market decision when the R&D sector is perfectly competitive (see Appendix A).

3.1. The social planner's problem in a large country

We start from the regime B equilibrium, where the home country is large and produces both goods, and the world price p equals the autarky price at home, a_1/a_2. Regime B is an important case for us, since it resembles the optimal R&D decision in a closed economy. It is also a simple one since technological improvement does not change the trade regime in this case. First the representative consumer chooses a consumption bundle (x_1, x_2), given R&D input (d_1, d_2) and prices (p, w); then the social planner chooses the R&D input (d_1, d_2) to maximize utility. Using the envelope theorem, it is straightforward to show that this two-stage maximization problem is equivalent to the social planner's problem of maximizing utility by choosing (x_1, x_2, d_1, d_2), that is,

$$\max_{x_1,x_2,d_1,d_2} u(x_1,x_2) = x_1^{\beta} x_2^{1-\beta} \tag{7}$$

$$\text{s.t.,} \quad p_1x_1 + p_2x_2 = w(L-d_1-d_2) \quad \text{and} \tag{8}$$

$$p_i = wa_i' = \frac{wa_i}{1+\theta d_i} \quad \text{for } i = 1,2, \tag{9}$$

where Eq. (8) is the budget constraint, while Eq. (9) is the equilibrium pricing condition. Substituting Eq. (9) into Eq. (8), the first-order conditions are then given by

$$\frac{\partial u(x_1,x_2)}{\partial x_i}=\lambda p_i \tag{10}$$

$$w+\frac{wx_i\partial a_i'}{\partial d_i}=0, \tag{11}$$

where λ is the Lagrange multiplier. Note that the social planner is constrained by the market wage rate w and equilibrium condition (9).

Eq. (11) highlights the costs and benefits of R&D. The first term in Eq. (11) is the marginal cost of R&D, while the second term is the marginal gain. The optimal level of R&D for sector i depends on both the research productivity θ, and the equilibrium output x_i. The higher the research productivity, the larger the marginal gain. Since one unit of ideas benefits x_i units of output, the more the equilibrium output x_i, the larger the marginal benefit. If the consumer's expenditure share in sector i is larger, or the country is more specialized in sector i (producing more x_i than the autarky output) in an open economy, the research input for sector i will be greater. It is interesting to note that the above results are very different from the conclusion reached by Eaton and Kortum (2001, page 15, in their studies of *uniform* technological improvement) that "...research intensity does not depend on country size, research productivity, or openness."

Solving the first-order condition gives optimal R&D inputs:[3]

$$d_1^{\mathrm{B}}=\frac{\beta\theta L-2(1-\beta)}{2\theta},\ d_2^{\mathrm{B}}=\frac{(1-\beta)\theta L-2\beta}{2\theta} \tag{12}$$

We then substitute Eq. (12) into Eq. (6) and obtain the optimal technology:

$$a_1'=\frac{2a_1}{(\theta L+2)\beta}\text{ and }a_2'=\frac{2a_2}{(\theta L+2)(1-\beta)}. \tag{13}$$

The optimal rates of technological improvement, defined as $(a_1/a_1', a_2/a_2')$, are proportional to consumers' expenditure share (β, $1-\beta$). That is, it is optimal to improve technology at a higher rate in the sector on which consumers spend more.

In trade regime B, sector 2 is the import sector at home. If $\beta<\frac{1}{2}$, the optimal strategy is relatively *import-biased*. The world relative price after technical progress at home is

$$\frac{a_1'}{a_2'}=\left(\frac{a_1}{a_2}\right)\left(\frac{1-\beta}{\beta}\right)>\frac{a_1}{a_2}, \tag{14}$$

which implies that the terms of trade in the foreign country deteriorate. Therefore, welfare in the foreign country decreases.

3.2. The case of a small country

We now turn to regime B*, in which the home country is a small country. Under this regime, technological changes in the home country may lead to regime changes. Also, it is possible for the home country to improve its technology to such an extent that it becomes a large country. If so, the equilibrium moves from regime B* to regime S, or even regime B. Thus, a complete analysis will require comparing the welfare levels in each possible regime. For simplicity, we assume that the home country remains a small country after the technological improvement. However, it is allowed to reverse its comparative advantage by investing in R&D in the import sector. Such an *import-biased* technological improvement, however, is not optimal, as we will show below.

If *export-biased* technological improvement is chosen, the home country specializes in producing good 1. The budget constraint (8) becomes $p_1x_1+p_2x_2=w\,(L-d_1)$, and the post-improvement technology parameters are $a_1'=\frac{a_1}{1+\theta d_1}$ and $a_2'=a_2$. Solving the first-order conditions gives the optimal R&D input:

$$d_1^{\mathrm{B}^*}=\frac{\theta L-1}{2\theta}. \tag{15}$$

Investment in R&D in the import sector is useless unless it is specialized in sector 2 after technological progress. Assuming it does so, we have $a_2'=\frac{a_2}{1+\theta d_2}$ and $a_1'=a_1$. The optimal solution is

$$d_2^{\mathrm{B}^*}=\frac{\theta L-1}{2\theta}. \tag{16}$$

For *import-biased* technological improvement to be effective, the home country must reverse its comparative advantage. If $d_2^{\mathrm{B}*}$ is not sufficiently large to accomplish this, the home country needs to input $d_2>d_2^{\mathrm{B}*}$ to improve technology in sector 2. Nevertheless, $u(x_1(d_2^{\mathrm{B}*}), x_2(d_2^{\mathrm{B}*}))$ is the highest utility that can be reached if *import-biased* technological improvement is chosen.

[3] The country size is assumed to be sufficiently large $L\geq max\left\{\frac{2(1-\beta)}{\theta\beta},\frac{2\beta}{\theta(1-\beta)}\right\}$, so that R&D input in each sector is nonnegative. With some computations, we show that the second-order condition for the maximization problem holds. The proof is available from the authors upon request.

Substituting Eqs. (15) and (16) into the indirect utility function, we have

$$\frac{u\left(x_1\left(d_1^{B^*}\right),x_2\left(d_1^{B^*}\right)\right)}{u\left(x_1\left(d_2^{B^*}\right),x_2\left(d_2^{B^*}\right)\right)}=\frac{a_2a_1^*}{a_1a_2^*}=\frac{a_1^*/a_2^*}{a_1/a_2}>1. \tag{17}$$

The inequality (17) comes from the comparative advantage assumption (1). Thus, *import-biased* technological improvement cannot be optimal for a small country.

A few remarks are in order. First, solutions (12) and (15) clearly indicate that the home country should invest more in R&D if its research productivity is higher. Second, research intensity is related to openness. Consider a thought experiment in which a small home country moves from autarky to free trade. It invests d_1^B in autarky in sector 1 but $d_1^{B^*}$ in free trade. Our result indicates that $d_1^{B^*}>d_1^B$, that is, trade openness leads the country to do more research in the sector in which it is more specialized. Finally, d_i^B/L in the large-country case and $d_1^{B^*}/L$ in the small-country case are all increasing in L. Therefore, it is optimal for larger countries to invest more in R&D per capita. We summarize our results in the following theorem:

Theorem 2. *A). Research input increases with research efficiency. In an open economy, countries do more research in the sector in which they are more specialized. Larger countries invest more in R&D per capita. B) For a small country, it is optimal to choose export-biased technological improvement, which benefits the foreign country. C) The optimal strategy for a large country, however, is to improve the technology at a higher rate in the sector on which consumers spend more. It hurts the foreign country if consumers at home spend more on the importable good.*

R&D per capita is determined by the first-order condition (11). Dividing both sides of the condition by L, we have

$$\frac{w}{L}=-\frac{wx_i}{L}\frac{\partial a_i'}{\partial d_i}\iff\frac{d_i}{L}=\left(1-\frac{d_i}{L}\right)\left[\frac{x_i}{(L-d_i)/f(d_i)}\right]a_i\left[-\frac{d_i\partial f(d_i)}{f(d_i)\partial d_i}\right]\iff\frac{d_i}{L}=\frac{\overline{x_i}a_i\Phi_i(d_i)}{1+\overline{x_i}a_i\Phi_i(d_i)}, \tag{18}$$

where $f(d_i)=1/(1+\theta d_i)$ is the production function of R&D, $\overline{x_i}=\frac{x_i}{(L-d_i)/f(d_i)}$ is the output per effective labor in production sectors, and is a constant. $\Phi_i(d_i)=-\frac{d_i\partial f(d_i)}{f(d_i)\partial d_i}$ is the elasticity of R&D with respect to the labor input. The marginal cost of R&D per capita, w/L, reduces proportionally to the increase in country size L. Whether optimal R&D per capita increases depends, therefore, on whether the marginal benefit of R&D increases more than proportionally to the increase in L. As country size L becomes larger, R&D input d_i increases. If $\Phi_i(d_i)$ increases in d_i, which holds in our setup since $\Phi_i(d_i)=\frac{\theta d_i}{1+\theta d_i}$, R&D per capita, $\frac{d_i}{L}$, must rise as d_i increases.

In summary, R&D elasticity $\Phi_i(d_i)$ determines R&D per capita. When $\Phi_i(d_i)$ is an increasing (constant, or decreasing) function of R&D input, the marginal benefit of R&D increases more than proportionally (proportionally, or less than proportionally) to the increase in country size. This implies that optimal R&D per capita increases (remains constant, or decreases) as the country becomes larger. Eaton and Kortum (2001, 2006) study R&D intensity in steady state growth and conclude that research intensity does not depend on country size. Their result may be viewed as a limit of our static model. Note that, in the limit ($L\to\infty$), our R&D per capita also converges to a constant.

3.3. When will a "catching-up" strategy be optimal?

Our final investigation examines regime S trade. As we have discussed in Section 2.1, $\frac{a_2^*}{a_2}\le E=\frac{\beta L^*}{(1-\beta)L}<\frac{a_1^*}{a_1}$ in regime S, and the home country is completely specialized in producing good 1. The home country can choose to reduce a_1, which does not change the trade regime. On the other hand, a sufficiently large *import-biased* technological improvement (reduction in a_2) can switch the trade regime from S to B. Within the regime B trade, the home country then improves technology in both sectors following the rule of Eq. (13), which is labeled as a "catching-up" strategy.

Instead of completely relying on imports in sector 2, the home country may try to catch up in the import sector and become self-sufficient in both goods.[4] The *export-biased* strategy has an adverse terms of trade effect. Moreover, Eq. (11) indicates that the marginal benefit of R&D in sector 1 declines. On the other hand, *import-biased* technical progress improves the terms of trade, but the labor spent in filling the gap between $\frac{a_2^*}{a_2}$ and $E=\frac{\beta L^*}{(1-\beta)L}$ has no effect on the economy and is therefore a waste of resources. On the demand side, technological improvement in sector 2 is more desirable if consumer's expenditure share in good 2, $1-\beta$, is larger. We formally derive a set of sufficient conditions in Appendix B, summarized as follows:

$$\beta<0.3494 \tag{19}$$

$$L>\frac{2(1-\beta)}{\theta\beta} \tag{20}$$

$$a_2<\overline{a}_2(L), \tag{21}$$

where

$$\overline{a}_2(L)=\frac{(1-\beta)^2a_2^*}{4\beta L^*\theta}\left[\frac{\beta^\beta(L\theta+2)^2}{(L\theta+1)^{2\beta}}\right]^{1/(1-\beta)} \tag{22}$$

4 The catching-up strategy has been a controversial policy in economic development. On the one hand, implementations of the catching-up strategy in 1950s and 1960s by many developing countries are generally not viewed as successful; on the other hand, the success of the catching-up strategy used in the automobile industries of Japan and South Korea is impressive.

Conditions (20) and (21) ensure that the distance between $\frac{a_2^*}{a_2}$ and $E = \frac{\beta L^*}{(1-\beta)L}$ is not too large, so that the *catching-up* strategy is not too costly, while condition (19) requires that the import sector be sufficiently large. Summarizing, we have the following

Theorem 3. *When both countries are fully specialized, the catching-up strategy is optimal if the expenditure share in the import sector is sufficiently large, the country is relatively large, and the technology in the import sector is relatively advanced.*

4. The Hicks path of technological improvement: discussion and conclusion

In analyzing the United States' technological improvement in the nineteenth and twentieth centuries, Hicks proposed two stages of technological improvement: countries start with *export-biased* technological improvement, and then "... the process passes into its second stage – notice that it is still a stage of development for the world economy, taken as a whole – in which the lead is taken by new centers, which are now making improvements that are *import-biased* (Hicks, 1953, pp 130)." Hicks noticed that Western Europe was not the first metropolis of trade and industry that had suffered from competition from new lands: the same elements were present in the decline of Greece, and in the rise of Britain at the expense of the Flemish and Italian centers in the fifteenth and sixteenth centuries. Hicks' two-stage path in technological improvement seems to be not just a historical phenomenon. Are emerging markets like China and India still in Hicks' first stage of development now? Will emerging markets move to the second stage? If so, when will they move? What will be the effect on the existing centers in this globalized age if emerging markets do move on to the second stage? Our analysis is only a beginning in the explanation of these extremely important issues.

To simplify the analysis, we make some restrictive assumptions. Although the Cobb–Douglas utility function is not essential to our results, it helps to keep the analysis tractable. We also assume a simple R&D function and that the efficiency of R&D is identical across sectors. The strategic interactions in R&D between the two countries are not studied. We do not consider imperfect competition, firm heterogeneity, or trade costs. The hard part of this analysis is the discrete change of trade regimes. Eaton and Kortum (2002) and Alvarez and Lucas (2005) provide a tractable continuum version of the Ricardian model. It would be worthwhile to investigate the optimal strategy in their version of the Ricardian model, which we leave for future studies.

Appendix A

In this appendix, we show that the social planner's optimal strategy for technological improvement is equivalent to the decentralized market decision when the R&D sector is perfectly competitive.

Consider an R&D sector that produces ideas. Firms in the R&D sector sell n_i ideas to manufacturing firms in sector i. Let the production function for ideas be $n_i = \theta d_i$, where θ measures research productivity and is assumed to be identical for sectors 1 and 2. After buying ideas, the technology in sector i becomes

$$a_i' = \frac{a_i}{1+n_i}. \tag{23}$$

The R&D firms charge a royalty of rn_i per unit of output produced in sector i. The total cost for firms in sector i, therefore, becomes

$$c_i = rn_i x_i + wa_i' x_i = (rn_i + wa_i')x_i. \tag{24}$$

Firms in sector i choose the number of ideas, n_i, to minimize the marginal cost of production, which gives the first-order condition as follows:

$$r + \frac{w\partial a_1'}{\partial n_i} = 0 \tag{25}$$

Let there be free entry and exit in the R&D sector so firms earn zero profit; this requires

$$rx_i n_i - wd_i = \left(rx_i - \frac{w}{\theta}\right)n_i = 0. \tag{26}$$

Substituting Eq. (26) into (25) and noting that $n_i = \theta d_i$, we immediately see that Eqs. (25) and (11) are identical. Now, manufacturing firms set the goods price equal to the marginal cost so that

$$\tilde{p}_i = rn_i + wa_i'. \tag{27}$$

Applying Eq. (27) to the budget constraint and noting that workers in the R&D sector and manufacturing sectors all earn wage w, we have

$$\tilde{p}_1 x_1 + \tilde{p}_2 x_2 = wL \Longleftrightarrow wa_1' x_1 + wa_2' x_2 = w(L - d_1 - d_2), \tag{28}$$

where Eq. (26) has been used to derive the second equality in Eq. (28). In a decentralized market, the consumer's first-order condition is the same as Eq. (10). It can be clearly seen, therefore, that the equilibrium conditions in the decentralized market, Eqs. (10), (25), and (28) are identical to that in the social planner's problem, Eqs. (10), (11), and (8).

Appendix B

In this appendix, we formally derive sufficient conditions for the catching-up strategy to be optimal in regime S trade. Conditions under which the catching-up strategy is optimal are

$$\frac{a_2^*}{a_2} < \frac{\beta L^*}{(1-\beta)L} < \frac{a_1^*}{a_1} \tag{29}$$

$$a_2 < \frac{(1-\beta)^2 (L\theta+2)^2 a_2^*}{4\beta L^* \theta} \tag{30}$$

$$L > \max\left\{\frac{2(1-\beta)}{\theta\beta}, \frac{2\beta}{\theta(1-\beta)}\right\} \tag{31}$$

$$u^{\mathrm{B}}\left(d_1^{\mathrm{B}}, d_2^{\mathrm{B}}\right) > u^E\left(d_1^E\right). \tag{32}$$

Inequality (29) ensures that the trade regime is S. Condition (30) makes sure that the trade regime switches from S to B. Condition (31) ensures that the country improves technology in both sectors. Finally, condition (32) requires that the utility of the catching-up strategy be greater than that of the *export-biased* strategy. The utility of the *export-biased* strategy can be derived as

$$u^E(d_1) = \frac{\beta L^{*1-\beta}}{a_1^\beta a_2^{*1-\beta}} (L-d_1)^\beta (1+\theta d_1)^\beta. \tag{33}$$

Maximizing $u^E\ (d_1)$ we obtain the optimal R&D input, $d_1^E = \frac{\theta L-1}{2\theta}$. With some computations, condition (32) can be written as

$$\frac{u^{\mathrm{B}}\left(d_1^{\mathrm{B}}, d_2^{\mathrm{B}}\right)}{u^E\left(d_1^E\right)} = \frac{\beta^{2\beta-1}(1-\beta)^{2-2\beta} a_2^{*1-\beta}(L\theta+2)^2}{(L^*\theta)^{1-\beta} a_2^{1-\beta} 2^{2-2\beta} (L\theta+1)^{2\beta}} > 1. \tag{34}$$

Conditions (29), (30) and (32) are combined as

$$\frac{(1-\beta)La_2^*}{\beta L^*} < a_2 < \min\left\{\frac{(1-\beta)^2(L\theta+2)^2 a_2^*}{4\beta L^*\theta}, \frac{(1-\beta)^2 a_2^*}{4\beta L^*\theta}\left(\frac{\beta^\beta (L\theta+2)^2}{(L\theta+1)^{2\beta}}\right)^{1/(1-\beta)}\right\}.$$

We can show that the first term in the above curly brackets is greater than the second one, so that a sufficient condition for the above inequality is

$$\frac{(1-\beta)La_2^*}{\beta L^*} < a_2 < \frac{(1-\beta)^2 a_2^*}{4\beta L^*\theta}\left(\frac{\beta^\beta (L\theta+2)^2}{(L\theta+1)^{2\beta}}\right)^{1/(1-\beta)} \iff \underline{a}_2(L) < a_2 < \bar{a}_2(L) \tag{35}$$

In order for Eq. (35) to hold, we must have $\underline{a}_2(L) < \bar{a}_2(L)$. Computations reveal that $\underline{a}_2(L) < \bar{a}_2(L)$ if $\beta < 0.3494$, which proves that Eqs. (19), (20), and (21) are sufficient conditions for Eqs. (29), (30), (31), and (32). When $\beta < 0.3494$, it can be easily shown that $\frac{\partial \bar{a}_2(L)}{\partial L} > 0$.

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