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LEARNING BY DOING, THE TECHNOLOGY GAP, AND GROWTH*

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In contrast with other trade and growth theories in previous literature, I present a growth theory of trade-induced learning: Other things being equal, two conditions are essential for trade-induced learning. First, both exports and imports are equally important sources and are mutually reinforced in intensifying the learning process. Moreover, the nature or characteristics of these traded goods also influence the effect of learning. Second, trade openness is a prerequisite but not a sufficient condition for rapid growth. With whom one trades (one's trading partner) is a key factor in determining trade-induced technology spillover and hence in affecting enduring growth. Therefore, this trade-induced learning theory provides abundant and testable implications for the empirical study of trade and growth.

1. INTRODUCTION

Most recent endogenous growth models yield the conclusion that large or wealthier countries grow more rapidly than small or poorer countries (see Romer 1986, and Lucas 1988). However, the so-called newly industrialized economies (NIE), such as Taiwan, South Korea, Hong Kong, and Singapore, have experienced annual growth rates of per-capita income averaging about 7%, significantly greater than industrial economies' average of 2.6% for the period 1960–1988. One common feature of NIE is that they all adopted an outwardly oriented strategy during this period. Trade seems to have played an important role in their economic development. By using a time-series, cross-country analysis for developing countries, Harrison (1996) found general support for a positive association between growth and different measures of openness. Pack and Page (1994) similarly found that manufactured exports explain part of the East Asian success.[2]

In neoclassical exogenous growth models, trade has only a level effect. Although Krueger (1984) and Harberger (1984) advocated free trade to promote growth,[3] in the recent endogenous growth models Rivera-Batiz and Romer (1991a, 1991b),

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[2] See also Dollar (1992), Page (1994), and Helliwell (1995). Edwards (1993), Rodrik (1993), and Bradford (1994) survey the literature.

[3] See also World Development Report 1987, the World Bank, for support of the same view.

Grossman and Helpman (1990, 1991a), Stokey (1991), and Young (1991), among others, provide rationales for the long-run growth effects of trade.

Innovation and international knowledge spillover as engines of growth proposed by Rivera-Batiz and Romer (1991b), and Grossman and Helpman (1991b) seem to adhere better among developed countries. However, models of innovation and imitation between North and South (see Grossman and Helpman 1991c) yield the conclusion that the less-developed South never has the opportunity of growing more rapidly than the well-developed North; hence, a permanent gap persists.[4] Learning by doing (as in Stokey 1991, and Young 1991) over a length of time can explain and mimic the chronological variation of production and trade patterns in the real world, involving introduction of new and technically sophisticated goods and discarding old and less sophisticated goods. Nevertheless, under free trade, Young (1991) concluded that the developed country experiences rapid technical progress at the expense of the less-developed country. Stokey (1991) also suggested that open trade has detrimental effects on less-developed countries. Dynamic learning by doing intensifies the initial pattern of comparative advantage (see Lucas 1988, Boldrin and Scheinkman 1988, and Matsuyama 1992). With the opening of trade, the less-developed country tends to specialize in low-technology goods, and the developed country tends to specialize in high-technology goods.

The models of endogenous growth mentioned above acknowledge a close correlation between trade and growth. However, they all fail to account how, by opening trade, developing or poor countries can grow rapidly and narrow the gap with developed countries as some NIE have done in recent decades.[5]

This study attempts to fill this gap by presenting a growth theory of trade-induced learning building on Young's (1991) model of bounded learning to address the real growth effect of trade and the evolution of international trade patterns. Trade-induced learning is the instrument of rapid growth for less-developed countries. In contrast to other models of trade and growth, two conditions (other things being equal) are essential in the trade-induced learning model. First, both exports and imports are important sources and are mutually reinforced in intensifying the learning process. The nature or characteristics of traded goods also influence the effect of learning. Second, openness of trade is a prerequisite but an insufficient condition for rapid growth. With whom one trades (one's trading partner) is a key

[4] Innovation induces imitation, and imitation stimulates innovation. The reason for the latter is that imitation by the South diminishes the number of firms in the North and, hence, increases marginal profits of existing firms in the North. This condition subsequently stimulates further innovation in the North.

[5] Some researchers argue that the benefits from backwardness may be strong enough to generate a tendency for leapfrogging. For example, Brezis et al. (1993) suggested a mechanism of leapfrogging whereby, under some conditions, lagging nations who have less experience and lower wages can apply certain advantages to adapt and to improve new techniques to break into the market. As for models of exogenous technological change, some authors have also notified the possibility of convergence phenomenon; see Krugman (1979). As for models of technological catch-up, see Succar (1987) and references therein. Succar (1987) provided a formal analysis of the process of technological assimilation of a least developed country and emphasized the technical complementarity between capital and technical capabilities in the research sector to shift outwards the achievable production function of modern sector.

factor that determines trade-induced technology spillover as it determines the level of technology from which one can learn. By this trade-induced and technology-driven mechanism, trade exerts real effects on the developing country's enduring growth. The parametric condition derived from the model implies that the process of catching up depends on the ratio of labor forces between the two trading countries. For a less-developed country with a small-sized labor force relative to that of the developed country participating in the production of learning goods, a larger technology gap and the degree of openness between the two countries is necessary to intensify the trade-induced learning effect. Results presented here suggest that the development strategy of a developing country is either to promote trade with the more advanced countries or to trade with countries whose technology level is slightly lagging behind.

The remainder of the paper is organized as follows: In Section 2, I investigate the process of trade-induced learning in detail and highlight the crucial factors of the process. In Section 3, a simple two-country model is developed under which goods and countries are indexed and ordered according to the technology level. The dynamic introduction of goods through learning by doing sustains growth and the presence of asymmetric international technology spillover accelerates the growth of the less-developed country. Concluding remarks and discussion of the possible policy and empirical implications are presented in Section 4.

2. LEARNING BY DOING AND THE TECHNOLOGY GAP

The process of trade-induced learning by doing proposed in this paper has two crucial components. First, both exports and imports reinforce the learning process. Moreover, the nature or characteristics of these traded goods also influence the effect of learning. Second, opening of trade is a prerequisite but an insufficient condition to generate rapid learning. With whom one trades (one's trading partner) is a key factor for trade-induced learning. I investigate the essence of the trade-induced learning process, and subsequently incorporate this trade-induced learning technology into a simple two-country framework in Section 3.

2.1. *Importance of Exports and Imports in the Trade-Induced Learning Process.* Endogenous growth models, using new consumption goods (Grossman and Helpman 1991a) or new intermediate goods (Romer 1990) as the engine of growth, provide a channel for trade to have growth effects by importing new final or intermediate goods. The introduction of new consumption goods diminishes the cost of further research and development, and the introduction of new intermediate goods augments capital formation. Both eventually lead to enduring growth. A major drawback of these models is that a country can grow forever by simply using all its foreign reserves to import greater varieties of final or intermediate goods, which seems unreasonable. In contrast, the trade effect in this work emphasizes learning through exporting refined domestic product lines to international markets and through technology diffusion fostered by export-led imports of technically sophisticated goods from advanced countries. A trade-induced learning process thus operates through both exports and imports.

Dissemination by journals and other media conveys information about new technology; however, the solid example of import goods facilitates and enlightens the process of learning. It is unconvincing that most developing countries enhance their production activities after learning a new technology through reading journals or articles. Many researchers have found that effectively assimilating modern technology acquired in the international market involves substantial resource costs.[6] Rather, it is observed that countries import new goods first, then produce them by themselves, and eventually export them. Reverse engineering is a good example of learning through exchange of goods.[7] One may argue that for the purpose of reverse engineering one sample product is sufficient; hence, no need arises for a large volume of trade. The international markets generally involve much uncertainty. However, the existing trade volume provides a signal of current and potential demand. Hence, this trade nexus confirms market information that subsequently generates the motive and incentive for reverse engineering or other forms of imitation or learning for the technology involved. It is also harder to start from zero and to invent something genuinely new than to add or to modify features to existing products. Japan is an example of a country that has an R&D stress more on development than on research.[8]

Exposing oneself to the competitive international market can not only exploit efficient production and scale economies by mass production to serve larger markets,[9] but also raise the demand for new technology. The World Development Report (1991, p. 89) stated that integration within the global trading system affects technological development by improving the supply of new technology and increasing the demand for new technology. Balassa (1967, p. 108) stated that foreign competition tends to stimulate research activity aimed at developing new products and improving methods. Increased trade may further contribute to the transmission of technical knowledge by increasing the familiarity of producers with new commodities and technological processes originating abroad. Development of efficient management and marketing skills is fostered through doing business with advanced countries. The return to entrepreneurial effort is increased by exposing oneself to foreign competition by inducing managers to eliminate inefficiency.[10] To enter the competitive international market, knowledge of the demand of foreign markets becomes essential, including knowledge about foreign buyers' specifications, quality and delivery conditions. To satisfy their requirements, foreign purchasers help and teach local export manufacturers to establish each stage of the production process and to improve management methods. For instance, in the case of original equipment manufacture (OEM), many brand-name companies in developed countries subcontract parts of their products to be manufactured in developing countries.

[6] See Teece (1977) and Ozawa (1966).

[7] See Mansfield and Romeo (1980) for evidence on reverse engineering.

[8] Ozawa (1966) estimated that one-third of Japan R&D was spent adapting imported technology to Japanese requirements.

[9] See Havrylyshyn (1990) for a survey of this literature.

[10] See Corden (174), and Martin and Page (1983) for this X-efficiency argument.

Keesing and Lall (1992) found that purchasers of NIE exports establish resident buying offices that provide advice on quality control and design alternations. Over time, the manufacturing firm gradually learns and acquires adequate technology to produce more sophisticated goods and to market its capacities as an attractive potential supplier of other foreign purchasers. Therefore, exporting enhances technology diffusion.[11] Expanding exports, in turn, guide the development of domestic production by accelerating the importing of more technologically sophisticated intermediate goods to meet the potential need of international markets. By using cross-country data for the period 1960–1985, Lee (1995) found that the ratio of imported to locally produced capital goods in the composition of investment has a significant positive effect on per-capita income growth rate across countries. However, Lee (1995) stressed the increase of efficiency of capital accumulation by importing the relatively cheaper capital goods from high-income countries, whereas, I emphasize the mechanism of export-driven import of sophisticated capital goods to streamline local production. This trade-induced learning spills over to other firms in the economy at large. An important feature of subcontracting is that foreign purchasers collaborate with local manufacturers, whom they teach but who do not actually own the knowledge connected with the innovations. No legal impediments prevent new or existing local firms from imitating and taking over the orders. The imitation is also in the interests of foreign purchasers who acquire additional sources of supply.

Without learning or with the same learning on all goods, according to the principle of comparative advantage less-developed countries invariably specialize in crude goods and developed countries specialize in refund goods. International trade forces the country to develop in the direction of what the country can execute when trade begins. However, learning on refined goods instead of crude goods enables a country to produce new refined goods. By using evidence from Singapore's electronics industry, Hobday (1994) indicated that technology was accumulated through gradual learning, rather than by leapfrogging. From the 1950s to the 1990s, the shifting of operation mode from OEM, to ODM (own-design manufacture) to OBM (own-brand manufacture) for East Asian NIE is a typical example of sequential learning. More importantly, opening trade, particularly trade with more advanced countries, accelerates the learning process through technology diffusion, and hence expedites enduring growth. This trade-induced learning effect on growth is described as follows.

Learning enables a country to produce new goods, and hence allows for the exporting of refined goods. Exporting of refined goods subsequently leads to absorption of new skills and experiences and thus generates the demand for new technology that is helpful for further domestic technology upgrading. This effect, in turn, speeds the need to import new technically sophisticated goods to streamline local production and enhance international competitiveness. Thus, *exporting and*

[11] In his microeconomic assessments of the Brazilian capital-goods industry focusing on the learning process in the export of manufactured goods, Teubal (1987) identified eleven endogenous spin-off mechanisms. The most common spin-off mechanism are related to manufacturing capabilities.

importing intensifies the learning process. This process of trade-induced technology diffusion provides the momentum for enduring growth to the less-developed country.

2.2. *Effective Degree of Openness: Learning Characteristics of Traded Goods and Trading Partners.* Two underlying key factors affect the trade-induced learning process described above: learning characteristics of traded goods, and the trading partner. The nature or learning characteristics of these traded goods generate varied influences for potential learning. For instance, manufactured goods have more learning potential than agricultural products, and electronic products provide more learning potential than food-processing products. Exports and imports provide the channel to learn, but trading partners determine the technological sophistication that one can learn. A technologically advanced country gains no learning from trading with a less technologically endowed country. Conversely, a less technologically endowed country can incur positive learning from a technologically advanced country by opening trade and gaining access to new technologies.[12] To trade with technologically advanced countries and hence to circulate new information not only widens one's knowledge but also stimulates one's learning process. Inventions and innovations require time, whereas exchange of goods through trade with technologically advanced countries provides concrete examples of current technology, which, in turn, stimulate learning through imitation, improvement, and newer innovations. In sum, opening trade is a prerequisite but an insufficient condition to generate rapid learning. Trading with technologically advanced countries accelerates the learning process of less-developed countries.

3. A SIMPLE TWO-COUNTRY MODEL

This section presents a simple model based on bounded learning by doing with asymmetric international technology spillover to illustrate the growth effect of trade and the evolution of trade patterns. The parametric condition under which the growth trajectory with catching up emerges, is also derived. Assuming a two-country world, country A denotes the advanced country and country B denotes the backward country, in which the technology level is greater in country A than in country B, that is, $T^A > T^B$. Labor in country A has a comparative advantage in producing more technically sophisticated goods and trade leads to complete specialization in which $w = w_A/w_B > 1$.[13] Trade between these two countries can profoundly affect patterns of trade and growth once asymmetric international technology diffusion is allowed to foster the process of learning by doing in the less technologically

[12] In sports such as tennis there is much for a poorly skilled player to learn by playing with a highly skilled player. I owe this example to Professor Gary Becker.

[13] Two possible partial specializations are available: one with $w^A = w^B$, country B specializes in producing only low-technology goods, and country A produces both types of goods; the other with $w^A > w^B$, country A specializes in producing only high-technology goods, and country B produces both types of goods. In the former case country B will not grow as no learning is generated from producing low-technology goods. In the latter case, country B can already produce goods with the same level of technology as country A. Both cases are rare and hence are not considered here.

endowed country. Other things being equal, the larger the technology gap and the greater the degree of openness between the two trading partners, the greater the international technology spillover.

3.1. *The Model.*

Technology and preferences. Like Wan (1975) and Young (1991), I assume that goods and countries can be ranked according to level of technological sophistication. Goods are indexed according to the sophistication of technology deemed necessary in production; in addition, a country's technology level is completely reflected in the spectrum of goods produced. Country A is said to be better endowed with technology than country B if the spectrum of goods produced in country A requires more advanced and sophisticated technology than those produced in country B. Hence, a continuum of goods and a rank of countries ordered by level of technology exists.[14] Let goods be indexed by $z, z \in [0, \infty)$, and ordered by their sophistication of technology in production (i.e., a greater z requires more advanced production technology). For simplicity, assume that labor is the only input in production and is immobile between the two countries. At any period there are constant returns to the production of each good. Both countries have the same production function for good z

$$(1) \qquad x^i(z) = \frac{l^i(z)}{a^i(z)} \quad \text{for } i = A, B,$$

in which $x^i(z)$, $l^i(z)$, and $a^i(z)$ are the output, labor input, and unit labor requirement of country i to produce good z, respectively. Labor is immobile across borders so that in both countries

$$(2) \qquad \int_0^\infty l^i(z)\, dz = L^i, \quad \text{for } i = A, B,$$

in which L^i is the total labor supply in country i.

Assume that the utility function is logarithmic

$$(3) \qquad U^i(c) = \int_0^\infty \log(c^i(z) + 1)\, dz, \quad \text{for } i = A, B,$$

in which $c^i(z)$ is the consumption of good z in country i and the consumer is endowed with one unit of labor.

Competitive equilibrium. The wage rate in country B (w^B) is chosen to be unity and all other prices are normalized to that. The budget constraint is

$$(4) \qquad \int_0^\infty p(z) c^i(z)\, dz \le w^i, w^i = 1 \quad \text{for } i = B, \quad \text{and} \quad w^i = w \quad \text{for } i = A,$$

[14] Later, the index of the most efficiently produced good is defined as the technology level of the country.

in which $p(z)$ is the price of good z. Solving the consumer's problem by maximizing utility given by equation (3) subject to the budget constraint in equation (4) yields

$$\frac{c^i(x)+1}{c^i(y)+1} = \frac{p(y)}{p(x)} \quad \text{for } x>0,\ y>0,\ i=A,B. \tag{5}$$

Thus, the demand function for good z is

$$c^i(z) = d_z(p, w^i), \quad \text{for } i=A,B. \tag{6}$$

The number of varieties that are potentially available can be infinitely large. However, the budget constraint sets an upper bound on the spectrum of goods consumed.

On the supply side, taking $p(z)$ and w^i given with each country allocating labor competitively among sectors, the profit maximization problem under simple linear technology becomes

$$\max \int_0^{\infty} \left[p(z) x^i(z) - w^i l^i(z) \right] dz \tag{7a}$$

$$\text{s.t. } x^i(z) = \frac{l^i(z)}{a^i(z)}. \tag{7b}$$

The supply rules of the problem are

$$\begin{aligned} x^i(z) &= 0 && \text{if } p(z) < w^i a^i(z), \\ x^i(z) &\in (0,\infty) && \text{if } p(z) = w^i a^i(z), \\ x^i(z) &= \infty && \text{if } p(z) > w^i a^i(z). \end{aligned} \tag{8}$$

As wage and technology levels are greater in country A, the unit cost curves in the two countries differ. According to the principle of comparative advantage, each country specializes in a distinct set of goods.

For country A,

$$x^A(z) \in (0,\infty) \quad \text{when } p(z) = w^A a^A(z) < w^B a^B(z); \tag{9a}$$

For country B,

$$x^B(z') \in (0,\infty) \quad \text{when } p(z') = w^B a^B(z') < w^A a^A(z'), \tag{9b}$$

in which z and z' belong to the potential set of goods technically producible for countries A and B, respectively.

At any time and for a given technology level, the competitive equilibrium prices and quantities are found by solving the market-clearing conditions for goods and labor:

$$D_z(p, w^A) + D_z(p, w^B) = X_z^A(p, w^A), \tag{10a}$$

$$D_{z'}(p, w^A) + D_{z'}(p, w^B) = X_{z'}^B(p, w^B), \tag{10b}$$

where $z \in [H^A, K^A]$, $z' \in [H^B, K^B]$, and $K^B \leq H^A$, and capitals D and X represent aggregate demand and supply. The sets $[H^A, K^A]$ and $[H^B, K^B]$ are the actual spectrum of goods produced in countries A and B, respectively.
Labor allocations in two countries are

$$\int_{z \in [H^A, K^A]} l^A(z)\, dz = L^A, \tag{11a}$$

$$\int_{z' \in [H^B, K^B]} l^B(z')\, dz' = L^B. \tag{11b}$$

At each time, $a^i(z)$ is fixed for given T^i and the competitive equilibrium described by equations (10a), (10b), (11a), and (11b) is instantaneously Pareto efficient, that is, it maximizes the welfare at time t of the representative consumer subject to production possibilities. However, in order to describe the dynamic temporal evolution of the Pareto-efficient allocations, the learning by doing mechanism must be specified.

Dynamic properties. Following Young's (1991) specification of bounded learning by doing, technology at any time can be generalized and described by the actual unit labor requirement curve, $a(z,T)$,[15] which has the property of
(a) $a(z,T) = \bar{a}(z)$, for $z \leq T$,
(b) $\bar{a}(z)$ decreases in z,
(c) $a(z,T)$ increases in z and decreases in T, for $z > T$,
where $\bar{a}(z)$ is the learning bound of good z. As Figure 1 reveals, at any time t, there is a U-shaped actual unit labor requirement curve for each country. The index of technical sophistication level T, corresponding to the lowest point of the U-shaped curve of unit labor requirement, is therefore defined as the technology level of the country. Consequently, there are goods in two sets in the economy. Low-technology goods are those of index smaller than T that have already exhausted their learning and, hence, reached their learning bounds. High-technology goods are those of an index greater than T that still enjoy learning.[16] Property (b) states that for those low-technology goods, the greater the technology index z of the good, the lower its learning bound, $\bar{a}(z)$. Property (c) states that for those high-technology goods, the greater the technology index of the good, the greater also the unit labor required for its production. Furthermore, over time, technology change shifts the unit labor requirement curve downward. For mathematical analysis, the U-shaped actual unit labor requirement curve, given by properties (a)–(c), is chosen to have the following functional form

$$a^i(z) = a(z, T^i) = \bar{a}(z) = \bar{a}e^{-z}, \qquad z \leq T^i, \text{ for } i = A, B, \tag{12a}$$

$$a^i(z) = a(z, T^i) = \bar{a}e^{z-2T^i}, \qquad z \geq T^i, \text{ for } i = A, B. \tag{12b}$$

[15] Where T is a function of t; hence, the time dimension is suppressed and T is used to express the current position of unit labor requirement curve of the country.
[16] Introducing learning bound generates asymmetric learning effects into two types of goods.

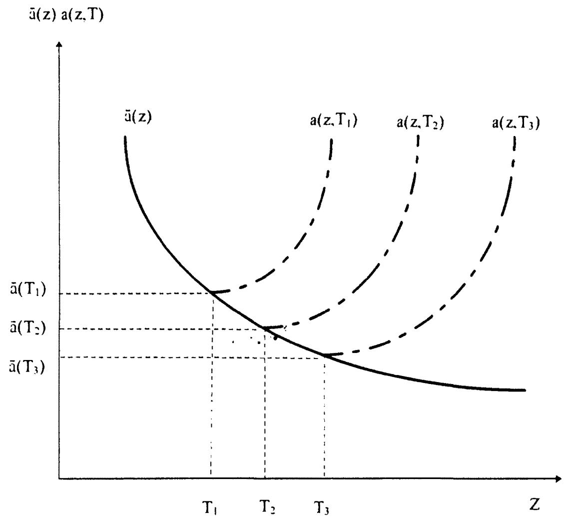

FIGURE 1

ACTUAL UNIT LABOR REQUIREMENT CURVE.

For each country, the U-shaped unit labor requirement curve is symmetric around its current technology level, $T^i(t)$, which corresponds to the most efficient technology in all goods production.[17] Economy-wide learning exists among those high-technology goods, and (most importantly, and different from Young 1991) in this paper trade intensifies the process of learning and, hence, shifts the right hand part of the unit labor requirement curve downward. According to the discussion in Section 2, the process of learning by doing is formulated and captured by

$$(13) \qquad \frac{dT^i}{dt} = G(T^j(t) - T^i(t)) \int_{T^i(t)}^{\infty} l^i(z,t)\, dz, \text{ for } i,j = A,B \text{ and } i \neq j,$$

The integral part on the right hand side of equation (13) represents the notion of bounded learning by doing. Goods with indices below $T^i(t)$ have already exhausted their learning, whereas economy-wide learning by doing occurs among those goods with indices above $T^i(t)$. Moreover, asymmetric trade-induced learning spillover exists between the two trading countries. This trade-induced learning effect is captured by the technology gap function G. For simplicity and to feature the trading partner effect, a linear form of G function is assumed, that is,

$$G(T^j(t) - T^i(t)) = 1, \qquad \text{if } T^j(t) - T^i(t) \leq 0,$$

$$G(T^j(t) - T^i(t)) = \omega_{ji}(t) \cdot [T^j(t) - T^i(t)] + 1, \qquad \text{if } T^j(t) - T^i(t) > 0,$$

[17] Notably, for complete specialization, i.e., $a(z,T^B) > w \cdot a(z,T^A)$ with $z > T^A$, under this specification it requires that the technology gap: $T^A - T^B > \ln(w)/2 > 0$.

in which $T^j(t) - T^i(t)$ in the gap function G represents the technology gap between trading partner j and the home country i at time t, and $\omega_{ji}(t)$ is the degree of openness of country i with respect to the trading partner j, taking both exports and imports and their learning characteristics into consideration. Therefore, the technology gap function G, which captures the notion in Section 2, distinguishes between partners with different technology levels: a lower technology partner from whom there is no trade-induced learning, and a higher technology partner from whom the greater the technology level and the degree of trade openness implies the greater the trade-induced learning. From equation (12b), we have

$$\frac{\partial a(z,T^i)/\partial t}{a(z,T^i)} = -2\frac{dT^i(t)}{dt}, \quad \text{for } i = A, B.$$

Over time, technology change due to learning by doing shifts the unit labor requirement curve downward.

Notably, in the dynamic equilibrium, however, wages, good prices, and thus demand and supply are endogenized and are a function of technology and the size of the labor force. Depending on the relative technology gap in the two countries, two types of equilibria—wide-gap and narrow-gap equilibria—may arise.

3.2. *Wide-Gap Equilibrium.* Wide-gap equilibrium is an equilibrium in which the technology gap results in that some goods with indices between T^B and T^A are not produced by both countries, i.e. the production sets of the two countries are disjointed. There is a spectrum of goods not produced in either country. Recall from equations (3) and (5) that as all goods enter the utility function symmetrically, under free trade the representative consumer in both countries consumes goods symmetrically about $T^A(t)$ and $T^B(t)$, the lowest point of unit cost curves $w \cdot a(z, T^A)$ and $a(z, T^B)$ respectively, until the budget is exhausted, as Figure 2 shows.

RESULT 1. Under wide-gap equilibrium, the sets of goods produced by both countries are fully determined by the relative wage w of the two countries, that is

$$(14) \quad \int_{H^A}^{K^A} w\left[a(H^A,T^A) - a(z,T^A)\right] dz + \int_{H^B}^{K^B}\left[a(H^B,T^B) - a(z',T^B)\right] dz' \le w.$$

PROOF. See the Appendix.

Goods indexed between K^B and H^A are not produced by either of the two countries. The spectrum of goods consumed in country A therefore consists of $[H^A(t), K^A(t)]$ of local goods and $[H^B(t), K^B(t)]$ of imported goods. Equation (14) is the consumer's budget constraint in country A. Similarly, the budget constraint of country B is written

$$(15) \quad \int_{h^A}^{k^A} w\left[a(h^B,T^B) - a(z,T^B)\right] dz + \int_{h^B}^{k^B}\left[a(h^B,T^B) - a(z',T^B)\right] dz' \le 1,$$

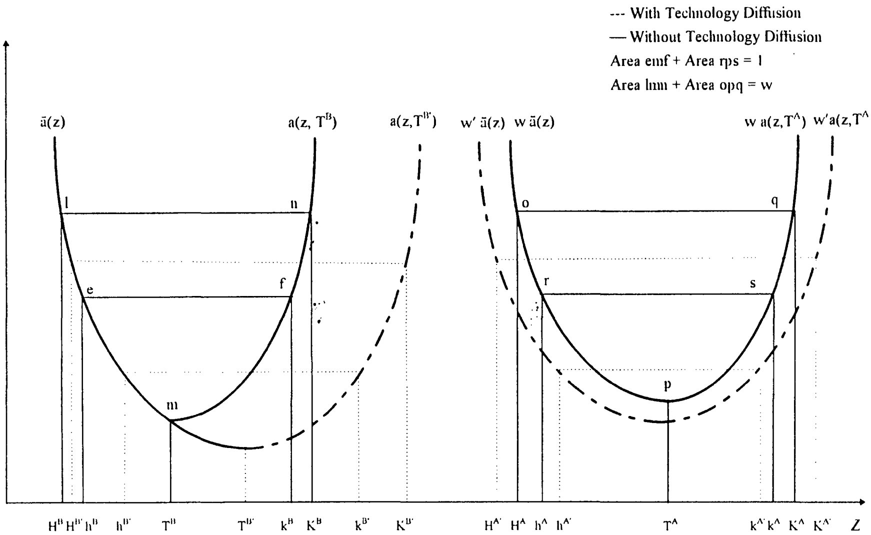

FIGURE 2

WIDE-GAP EQUILIBRIUM.

in which $[h^B(t), k^B(t)]$ and $[h^A(t), k^A(t)]$ are the set of locally produced goods and imported goods consumed by country B, respectively. As the relative wage $w > 1$, $[h^B(t), k^B(t)]$ is smaller than $[H^B(t), K^B(t)]$ and $[h^A(t), k^A(t)]$ is smaller than $[H^A(t), K^A(t)]$. Therefore, country B exports some crude and refined goods that are not consumed locally, and consumes some imported goods with most efficient production but not the state-of-art technology of country A. Let

$$\lambda^i(t) = T^i(t) - H^i(t) = K^i(t) - T^i(t), \text{ for } i = A, B.$$

Equation (14) implies that[18]

$$0 < \ln\left[\bar{a} e^{\lambda^A}(2\lambda^A - 2) + 2\bar{a}\right] < T^A, \tag{16}$$

and

$$0 < \ln\left[\bar{a} e^{\lambda^B}(2\lambda^B - 2) + 2\bar{a}\right] < T^B + \ln(w). \tag{17}$$

In equilibrium, the relative wage w is a function of technology level (T^A, T^B).

RESULT 2. The relative wage $w(w^A/w^B)$ is a strictly decreasing (increasing) function of $T^B(T^A)$, that is, $dw/dT^B < 0$ $(dw/dT^A > 0)$.

PROOF. See the Appendix.

[18] The Appendix provides the derivation of equations (16) and (17).

RESULT 3. Over time, the spectrum of goods produced and consumed in both countries evolves by adding more technically sophisticated goods and eliminating less technically sophisticated goods. Furthermore, the range of new goods introduced is greater than that of old goods abandoned.

PROOF. See the Appendix.

RESULT 4. The variety and quantity of goods consumed with respect to the current technology level in both countries increase over time.

PROOF. See the Appendix.

LEMMA 1. *For each country, per-capita real GNP grows at the same rate as technology.*

PROOF. See the Appendix.

PROPOSITION 1. *In the presence of trade-induced learning by doing, by more open trade with a more advanced country, the less developed country can actually grow more rapidly than the developed country, provided that the following condition is true*

$$\omega_{AB} \cdot \left[T^A(t) - T^B(t)\right] > \frac{L^A(t) - L^B(t)}{L^B(t)}.$$

PROOF. See the Appendix.

The condition in Proposition 1 always holds for $L^B(t) \geq L^A(t)$. However, even under the situation where $L^B(t)$ is less than $L^A(t)$, with a positive trade-induced growth effect from more opening trade with a more advanced country, the small or poor country can still grow faster than the large or wealthier country provided that the condition in Proposition 1 is satisfied. The interpretation of scale effect of population deserves further exposition. Notably, it is the number of workers engaged in the production of learning goods that matters, not the total population. Other things being equal, after opening trade with the developed country, a developing country with a larger population benefits more from learning than one with a smaller population as the trade may induce the former to have a larger workforce producing learning goods. Total population thus becomes relevant in determining a country's long-run growth.[19] Furthermore, as the proportion of population in producing learning goods is the same under wide-gap equilibrium for both countries, the condition required for the less developed country to catch up and grow faster is fully determined by the relative labor ratio compared with the degree of openness and technology gap between the two countries. Other things being equal, for a less developed country with a small-sized labor force relative to

[19] Notably, as pointed out by Lucas (1993), a link between the level of employment and the rate of growth of productivity is a feature of any learning by doing theory. However, Lucas (1993) and Matsuyama (1992) suggested that the implied scale effect should be considered as the effective stock of human capital instead of the size of population.

that of the developed country participating in the production of goods still enjoying learning, a larger technology gap and the degree of openness between the two countries are required to intensify the trade-induced learning effect.

Production, consumption and trade patterns. In the presence of trade-induced technology diffusion, the further downward shift of $a(z, T^B)$ may drastically alter the spectrum of production and consumption in both countries compared with the circumstance without an effect. The technology level in country B advances from T^B to $T^{B'}$ as Figure 2 shows. The magnitude of the downward shift of the $a(z, T^B)$ curve, as learning decreases the unit labor requirement for goods maintaining learning by doing, depends on how openly country B trades with country A, ω_{AB}, and on the current technology gap between the two countries, $T^A(t) - T^B(t)$. As the relative wage is a function of the technology level, Result 2 confirms that increasing T^B also diminishes the unit labor requirement curve of country A everywhere (see Figure 2). Country B produces goods from $H^{B'}$ to $K^{B'}$ and consumes $h^{B'}$ to $k^{B'}$ of local goods and $h^{A'}$ to $k^{A'}$ of imported goods, whereas country A produces goods from $H^{A'}$ to $K^{A'}$ and consumes $H^{A'}$ to $K^{A'}$ of local goods and $H^{B'}$ to $K^{B'}$ of imported goods. With asymmetric technology diffusion, the spectra of domestic consumption and production in country B are widened and shifted toward a more technology-intensive basis. However, the variation of spectra of domestic consumption (production) and exports in country A are ambiguous. The larger the variation of a relative wage due to trade-induced technology progress of country B implies a more likely increase of the spectrum of local consumption and production of country A and also a greater spectrum of exports to country B. Figure 2 depicts the case of an increasing spectrum of local consumption (production) and a decreasing spectrum of exports for country A.

In sum, the consumption pattern in both countries becomes altered. Country B tends to consume more varieties of goods locally produced and may consume a greater or narrower spectrum of goods produced abroad that depends on the variation of relative wage.[20] In contrast, country A may consume more or less varieties of goods domestically produced but consume more imported goods from country B, particularly the most technically advanced goods of country B. In terms of production, through international technology spillover, the country less endowed with technology accelerates by producing more technically sophisticated goods. Whereas the advanced country may expand or shrink the production spectrum in both crude and refined goods.

Here, the evolution of a trade pattern is observed in which country B imports current but not the most technologically advanced goods from country A and exports goods, some of which are merely for consumption in country A. Over a period of time, the composition of exports shifts in the direction of more technically sophisticated goods. The trade-induced technology spillover plays a prominent role in fostering the production set of the less developed country. Consequently, a country can produce and export goods it could not do so before. This leads to Proposition 2.

[20] It is common, particularly during the early period, that the spectrum of imports from country A shrinks as shown in Figure 2.

PROPOSITION 2. *In the presence of trade-induced learning by doing, the process of economic development in the less developed country is characterized by production, consumption, and trade patterns all being upgraded along the technology ladder.*

Although the gap narrows over a period of time, the spectrum of goods produced in the less developed country expands and the trade-induced technology spillover can still be significant for a considerable period. Nevertheless, as the less developed country ascends the technology ladder eventually, the narrowing of the gap dominates and scope for trade-induced technology spillover contracts. Therefore, the trade-induced technology diffusion effect on growth weakens.

3.3. *Narrow-Gap Equilibrium.* Narrow-gap equilibrium is an equilibrium in which the technology gap renders that all goods with technology indices having fallen between T^A and T^B are produced by the two countries. Under a narrow-gap equilibrium, country B is sufficiently near country A in a technology level that the largest value of z in B is just beside the smallest value of z in country A. The production sets of the two countries are not disjointed. However, the sets of goods produced by both countries are still determined by the relative wage w, and the least upper bound (greatest lower bound) M of production set of country B (A) depends on the intersection of two unit cost curves, $a(z,T^B)$ and $w\ \bar{a}(z)$, of the two countries. According to comparative advantages, more labor is employed in producing high-technology goods in country A and more labor is employed in producing low-technology goods in country B. Let sets $[H^B, M]$ and $[M, K^A]$ be the two production sets of country B and A, respectively. For goods indexed at technology level M, $P(M,t) = a(M,T^B) = w \cdot \bar{a}(M)$, with $w = w^A/w^B$. Hence,

$$\bar{a}\,e^{M-2T^B} = w\bar{a}\,e^{-M}, \text{ or}$$

$$M - T^B = \frac{1}{2}\ln w.$$

Taking the derivative yields

$$\frac{dM}{dt} - \frac{dT^B}{dt} = \frac{1}{2w}\frac{dw}{dt}.$$

Thus

$$\frac{dM}{dt} - \frac{dT^B}{dt} \lesseqgtr 0, \text{ if } \frac{dw}{dt} \lesseqgtr 0.$$

The spectrum of goods still enjoying learning in country B depends on the variation of relative wages between the two countries. If over time country B's wage increases relative to country A's wage, as should be the case, then the spectrum of sophisticated goods in country B is expected to contract.

Technological variations in the two countries become

$$(18)\quad \frac{dT^A(t)}{dt} = \int_{T^A(t)}^{K^A(t)} l^A(z,t)\,dz > \frac{1}{2}L^A(t),$$

$$(19)\quad \frac{dT^B(t)}{dt} = \int_{T^B(t)}^{M(t)} \omega_{AB}(T^A(t) - T^B(t))l^B(z,t)\,dz + \int_{T^B(t)}^{M(t)} l^B(z,t)\,dz.$$

Therefore, the growth rate of per-capita GNP in country A exceeds $L^A(t)/2$, because after opening trade labor was forced to reallocate from a low-technology to a high-technology industry. In addition, more than half the labor force in country A is employed in producing goods while still enjoying learning.

With technology spillover, country B's unit cost curve, $a(z,T^B)$, shifts further down. The production set of goods still enjoying learning by doing upgrades along the technology ladder and captures the market of goods originally produced by country A. However, the spectrum of these goods is confined by the unit cost curve of goods that have already exhausted learning in country A, that is, $w\cdot\bar{a}(z)$. Although trade-induced diffusion effects upgrade the technology level, the production of refined goods in the less technology-endowed country is likely to contract under the circumstance of a small technology gap and increasing relative wages of country B, which shifts downwards $w\cdot\bar{a}(z)$ curve over time.

As in equation (19), the second term is less than $L^B(t)/2$; after trade labor was forced to reallocate from high-technology to low-technology industries and less than $L^B(t)/2$ is employed in producing high-technology goods. When the gap is narrowed, $T^A(t) - T^B(t)$ becomes small and also the range between T^B and M is likely to contract. Therefore, the trade-induced technology diffusion effect in the first term of equation (19) becomes less significant. Therefore, even in the presence of technology diffusion, the rate of technology change in country B is likely to be less than $L^B(t)/2$.[21] In the narrow-gap situation, the more-advanced country may actually grow rapidly at the expense of the less-advanced country. This result confirms the belief that the trading partner matters and a large technology gap is a sufficient condition to ensure that trade-induced technology diffusion enables a less-developed country to grow more rapidly than an advanced one.

PROPOSITION 3. *For two countries of equal size, a unique and persistent technology gap exists such that these two countries grow at the same rate. Furthermore, the persistent gap is smaller between the two countries and the corresponding growth rates of both countries are greater with a trade-induced technology spillover than without* (*see Figure* 3).

PROOF. See the Appendix.

[21] Without technology diffusion the rate of technology change in country B is invariably less than $L(t)^B/2$. However, there is a possibility in the situation $(dM/dt) - (dT^B/dt) < 0$ that with technology diffusion the rate of growth in country B may even be smaller than without the effect.

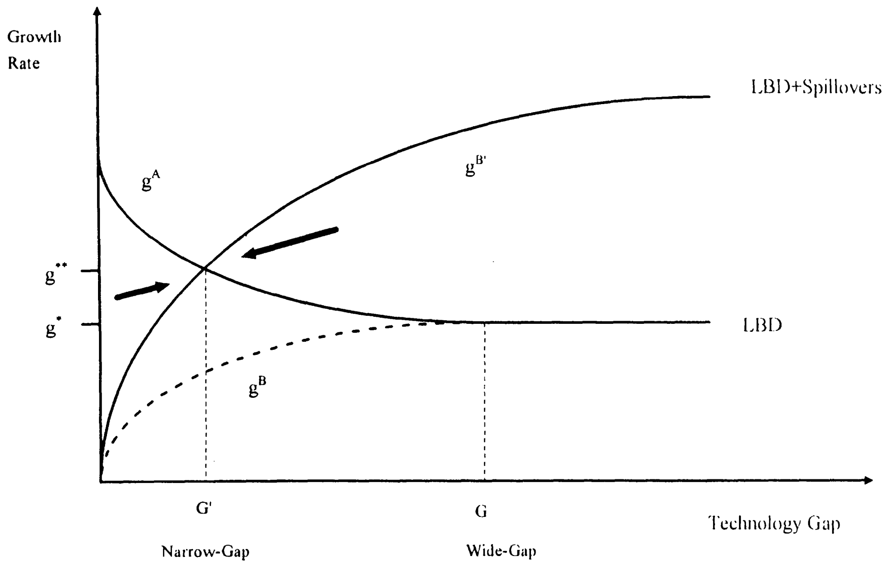

FIGURE 3

BALANCED GROWTH FOR TWO COUNTRIES WITH EQUAL SIZE. $g^{B'}$ AND g^B REPRESENT GROWTH RATES OF COUNTRY B WITH AND WITHOUT THE TRADE-INDUCED LEARNING EFFECT.

Notably, the condition of equal size for the two countries in Proposition 3 is only a sufficient not necessary condition to ensure that $dT^A/dt < dT^B/dt$ under wide-gap equilibrium and $dT^A/dt > dT^B/dt$ under narrow-gap equilibrium (see the Proof in the Appendix). Balanced growth can also be obtained when country size varies. For example, under wide-gap equilibrium from Proposition 1 a balanced growth path with a permanent gap exists if $\omega_{AB} \cdot [T^A(t) - T^B(t)] = [L^A(t) - L^B(t)]/L^B(t)$. Therefore, trade-induced technology spillover effects on growth can narrow, but cannot completely close, the gap.

4. DISCUSSION AND CONCLUDING REMARKS

As preferences are symmetric over goods, goods consumed are never eliminated from the production set. The effect of learning by doing, of decreasing cost of refined goods, generates new comparative advantages and forces the economy to evolve by adding new goods and abandoning old ones. This effect is similar in spirit to Assumption 3 in Stokey (1988). The main distinction is in the degree of spillover. Stokey (1988) assumed that economy-wide learning by doing occurs among all goods and that the cost effect of learning is greater for higher-index goods, that is, forward spillover is stronger than backward spillover. These two conditions ensure the introduction of new goods. In this analysis, two sets of goods are produced at each time t, low technology goods that have already exhausted learning and high technology goods that still enjoy learning. The rate of learning is required to be the same among the high technology goods. This weaker assumption is all that is needed to ensure the effect of introducing new goods and abandoning old goods and even causes a wider spectrum of new goods being introduced than of old goods being abandoned, as stated in Result 3.

In the presence of asymmetric international technology spillover, the less developed country can grow rapidly. The accelerating growth in the less developed country is characterized by further expanding new goods produced; to some extent, the most sophisticated goods being primarily for export. The positive effect of trade on growth for the less developed countries is most significant under a wide-gap situation, where the trading partner matters. The parametric condition for the less developed country to catch up and grow faster is fully determined by the relative labor ratio compared with the degree of openness and technology gap between the two countries. Other things being equal, for a less developed country with a small-sized labor force relative to that of the developed country participating in the production of goods still enjoying learning, a larger technology gap and degree of openness between the two countries are required to intensify the trade-induced learning effect. However, under a narrow-gap situation, the size of labor force participating in producing learning goods in the less developed country is always smaller than that in the developed country. The Stokey–Young proposition is therefore likely to hold. In that case, opening trade may cause a divergence of growth rate between the developed and the less developed countries.

I have presented a development strategy for the less developed country to begin to overtake and narrow the gap with the developed country. Other things equal, two conditions are essential in the model of growth through trade-induced learning by doing. First, both exports and imports are important sources and mutually reinforced in intensifying the learning process. Moreover, the nature or learning characteristics of these traded goods also influence the effect of learning. Second, trade openness is a prerequisite but an insufficient condition to accelerate growth. With whom one trades (one's trading partner) is a key factor in trade-induced technology diffusion and upgrading as it determines the level of technology from which one can learn. By this trade-induced and technology-driven mechanism, trade exerts real effects on the developing country's enduring growth.

As for policy implications, the following are crucial for a developing country to foster economic take-off and sustained growth: (a) to promote trade with technologically advanced countries, as these countries determine the level of technology from which the developing country can learn; or trade with countries whose technology level is similar but slightly lagging behind, as one can take the comparative advantage of the shifting labor force in producing more technology-intensive goods; (b) to relax trade restrictions on infant industry protection and to allow export-driven imports of sophisticated capital goods, thus expanding access to new technology and intensifying the learning process; (c) to promote technology transfer (e.g., subcontracting and licensing) and attract direct foreign investment and multinational enterprises on the production of goods with greater learning characteristics (e.g., machinery and equipment) aimed at the global market; (d) to provide a better environment (including information services) for technology diffusion among firms and industries, since economy-wide learning by doing is the impetus of economic growth; and (e) to encourage investment in human capital (e.g., education and on-the-job training), since a better-educated labor force absorbs new information faster and applies unfamiliar inputs or processes more effectively.

Among abundant and testable empirical implications of the model are the following: (a) By holding a country's characteristics constant, more open trade (exports plus imports) with the outside world implies a higher likelihood of stimulating growth via technology diffusion. Moreover, a larger technology gap with trading partners implies a greater potential for learning and growth. Therefore, the greater the trade with developed countries, the more likely a country is to thrive and grow faster. (b) Learning characteristics of traded goods matters. Trading goods with a greater extent of learning (e.g., compare manufactured goods with agricultural products) accelerates the effect of trade-induced learning and hence enduring growth. Empirical tests on what kinds of traded goods bearing the greatest learning effect and, hence, best explain a country's enduring growth, can thus be identified. (c) During the development process, sustained growth together with production, consumption, and trade patterns are all upgraded along the technology ladder. The trade pattern in less developed countries shifts toward exporting more technology-intensive goods and importing goods with current, but not the most current, technologies of advanced countries. In particular, a common phenomenon among these developing countries is that goods locally produced with the highest technology level are used mainly to export to advanced countries.

APPENDIX

A1. Proof of Result 1.

From equations (5), (9a) and (9b)

$$\text{(A.1)}\qquad \frac{c^i(x)+1}{c^i(y)+1}=\frac{a(y,T^i)}{a(x,T^i)}\quad \text{for } x,y\in[H^i,K^i],\quad i=A,B,$$

and

$$\text{(A.2)}\qquad \frac{c^A(z)+1}{c^B(z')+1}=\frac{a(z',T^B)}{w\cdot a(z,T^A)}\quad \text{for } z\in[H^A,K^A],\ z'\in[H^B,K^B],$$

where $[H^A,K^A]$ and $[H^B,K^B]$ are the sets of goods produced in country A and B, respectively, and $K^B<H^A$.

For country i at time t, $T^i(t)$ is the current technology level corresponding to the lowest cost. $H^i(t)$ ($K^i(t)$) is the greatest lower (least upper) bound of technical sophistication level of goods produced locally, that is, $c(H^i,t)=0$, and $c(K^i,t)=0$, $i=A,B$. Therefore from equation (A.1)

$$a(H^i,T^i)=a(K^i,T^i)=a(z,T^i)(c^i(z)+1),\text{ for } i=A,B.$$

Rearranging yields

$$\text{(A.3)}\qquad a(z,T^i)c^i(z)=a(H^i,T^i)-a(z,T^i),\quad \text{for } i=A,B.$$

The budget constraint of country A is

$$\int_{H^A}^{K^A} p(z)c^A(z)\,dz + \int_{H^B}^{K^B} p(z')c^A(z')\,dz' \le w^A, \tag{A.4}$$

and the zero-profit condition under competitive markets requires

$$p(z) = w^i a(z,T^i) \text{ for } \quad z \in [H^i, K^i], \quad i = A, B.$$

So the budget constraint can be written as

$$\int_{H^A}^{K^A} wa(z,T^A)c^A(z)\,dz + \int_{H^B}^{K^B} a(z',T^B)c^A(z')\,dz' \le w. \tag{A.5}$$

Substituting equations (A.3) into (A.5) leads to

$$\int_{H^A}^{K^A} w\big[a(H^A,T^A) - a(z,T^A)\big]\,dz + \int_{H^B}^{K^B}\big[a(H^B,T^B) - a(z',T^B)\big]\,dz' \le w.$$

This tells us that the area between $w \cdot a(H^A, T^A)$ and $w \cdot a(z, T^A)$ plus the area between $a(H^B, T^B)$ and $a(z', T^B)$ are equal to the relative wave w (see Figure 2). Under wide-gap equilibrium, the spectra of goods produced at time t in both countries, bounded intervals of $[H^A(t), K^A(t)]$ and $[H^B(t), K^B(t)]$, are fully determined by the consumer's budget constraint in country A. Q.E.D.

A2. Derivation of Equations (16) and (17). By decomposition, equation (14) implies that

$$0 < \int_{H^A}^{K^A}\big[a(H^A,T^A) - a(z,T^A)\big]\,dz < 1. \tag{A.6}$$

and

$$0 < \int_{H^B}^{K^B}\big[a(H^B,T^B) - a(z',T^B)\big]\,dz' < w. \tag{A.7}$$

Since

$$\begin{aligned}
&\int_{H^A}^{K^A}\big[a(H^A,T^A) - a(z,T^A)\big]\,dz \\
&\quad = a(H^A,T^A)[K^A - H^A] - 2\int_{H^A}^{T^A} \bar{a}e^{-z}\,dz \\
&\quad = \bar{a}e^{-H^A}(2\lambda^A) + 2\bar{a}\big[e^{-T^A} - e^{-H^A}\big] \\
&\quad = \bar{a}e^{-H^A}(2\lambda^A - 2) + 2\bar{a}e^{-T^A},
\end{aligned}$$

thus equation (A.6) becomes

$$0 < \bar{a}e^{-H^A}(2\lambda^A - 2) + 2\bar{a}e^{-T^A} < 1.$$

Multiplying $\exp(T^A)$ and then taking the logarithm of both side yields

$$0 < \ln\left[\bar{a}e^{\lambda^A}(2\lambda^A - 2) + 2\bar{a}\right] < T^A.$$

By the same token, equation (A.7) yields

$$0 < \ln\left[\bar{a}e^{\lambda^B}(2\lambda^B - 2) + 2\bar{a}\right] < T^B + \ln(w). \qquad \text{Q.E.D.}$$

A3. Proof of Result 2. As T^B increases and lowers the unit cost curve in country B, local consumption in country B will increase and import demand for foreign goods will be reduced. Since goods produced in country B become relatively cheaper than goods in country A, import demand of country A will increase. However, if $dw/dT^B \geq 0$, then due to the income effect, the import demand of country A will increase even more than before the increase in T^B. This is a contradiction since the new consumption bundle of country A will not be sustainable under the current technology of country A and neither will the balance of trade hold. By the same argument, $dw/dT^A > 0$. Q.E.D.

A4. Proof of Result 3. Differentiating equations (16) and (17) with respect to $T^A(t)$ and $T^B(t)$, respectively, gives

$$0 < \frac{\bar{a}e^{\lambda^A}(2\lambda^A - 2) + 2\bar{a}e^{\lambda^A}}{\bar{a}e^{\lambda^A}(2\lambda^A - 2) + 2\bar{a}} \frac{d\lambda^A}{dT^A} < 1,$$

and

$$0 < \frac{\bar{a}e^{\lambda^B}(2\lambda^B - 2) + 2\bar{a}e^{\lambda^B}}{\bar{a}e^{\lambda^B}(2\lambda^B - 2) + 2\bar{a}} \frac{d\lambda^B}{dT^B} < 1 + \frac{1}{w}\frac{dw}{dT^B} < 1.$$

Since

$$\frac{\bar{a}e^{\lambda^i}(2\lambda^i - 2) + 2\bar{a}e^{\lambda^i}}{\bar{a}e^{\lambda^i}(2\lambda^i - 2) + 2\bar{a}} > 1 \text{ for } \quad i = A, B,$$

hence

$$0 < \frac{d\lambda^i}{dT^i} < 1, \quad \text{for } i = A, B.$$

But $\lambda^i(t) = T^i(t) - H^i(t) = K^i(t) - T^i(t)$, thus

$$\frac{d\lambda^i}{dT^i} = 1 - \frac{dH^i}{dT^i} = \frac{dK^i}{dT^i} - 1, \quad \text{for } i = A, B.$$

Therefore

$$0 < \frac{dH^i}{dT^i} < 1, \text{ and } 1 < \frac{dK^i}{dT^i} < 2, \quad \text{for } i = A, B. \qquad \text{Q.E.D.}$$

A5. PROOF OF RESULT 4. Increasing variety of consumption has been proved in Result 3. As for the increase of quantity consumed, it is known that

$$c^i(T^i) = \frac{a(H^i)}{a(T^i)} - 1 = \bar{a}\,e^{T^i - H^i} - 1 = \bar{a}\,e^{\lambda^i} - 1, \quad \text{for } i = A, B.$$

Hence

$$\frac{dc^i(T^i)}{dT^i} = \bar{a}\,e^{\lambda^i}\frac{d\lambda^i}{dT^i} > 0, \quad \text{for } i = A, B, \qquad \text{Q.E.D.}$$

A6. PROOF OF LEMMA 1. The growth rate of real GNP per-capita can be defined as

$$g^i(t) = \frac{\int_0^\infty p(z,t)\,\partial X^i(z,t)/\partial t\,dz}{\int_0^\infty p(z,t) X^i(z,t)\,dz} - \frac{dL^i(t)/dt}{L^i(t)}, \quad \text{for } i = A, B, \tag{A.8}$$

where $X^i(z,t)$ is aggregate output of good z at time t for country i. By using the zero-profit condition $p(z,t) = w^i \cdot a(z, T^i)$, labor supply conditions

$$L^i(t) = \int_0^\infty a(z, T^i) X^i(z,t)\,dz,$$

and

$$\frac{dL^i(t)}{dt} = \int_0^\infty a(z,T^i)\frac{\partial X^i(z,t)}{\partial t}dz + \int_0^\infty \frac{\partial a(z,T^i)}{\partial t}X^i(z,t)\,dz, \quad \text{for } i = A, B,$$

and then substituting into equation (A.8) gives

$$\begin{aligned} g^i(t) &= \frac{-\int_0^\infty \partial a(z,T^i)/\partial t X^i(z,t)\,dz}{L^i(t)} \\ &= \frac{2\dfrac{dT^i(t)}{dt}\int_{T^i(t)}^{K^i(t)} a(z,T^i) X^i(z,t)\,dz}{L^i(t)} \\ &= \frac{2\dfrac{dT^i(t)}{dt}\left(\dfrac{1}{2}L^i(t)\right)}{L^i(t)} \\ &= \frac{dT^i(t)}{dt}, \quad \text{for } i = A, B. \end{aligned}$$

Thus, for each country, per-capita real GNP grows at the same rate as technology. Q.E.D.

A7. PROOF OF PROPOSITION 1. The rate of technology progress in country A is given by

$$\frac{dT^A(t)}{dt} = \int_{T^A(t)}^{K^A(t)} l^A(z,t)\,dz = \frac{1}{2}L^A(t). \tag{A.9}$$

Technology progress in country A is equal to half of the labor force, since there are $L^A(t)/2$ employed in producing goods still experiencing learning by doing, while the technology progress in country B is given by

$$\begin{aligned} \frac{dT^B(t)}{dT} &= \int_{T^B(t)}^{K^B(t)} \left[\omega_{AB}(T^A(t) - T^B(t)) + 1\right] l^B(z,t)\,dz \\ &= \int_{T^B(t)}^{K^B(t)} \left[\omega_{AB}(T^A(t) - T^B(t))\right] l^B(z,t)\,dz + \frac{1}{2}L^B(t) \\ &> \frac{1}{2}L^B(t). \end{aligned} \tag{A.10}$$

On the right-hand side of the second equality sign, the first term is the trade-induced technology spillover effect that depends on the degree of openness and the technology gap. The second term is the usual learning by doing effect. Country B learns and grows faster under trade-induced technology diffusion. Comparing equations (A.9) and (A.10) yields

$$\frac{dT^B}{dt} > \frac{dT^A}{dt} \quad \text{if } \omega_{AB}\cdot\left[T^A(t) - T^B(t)\right] > \frac{L^A(t) - L^B(t)}{L^B(t)}. \qquad \text{Q.E.D.}$$

A8. PROOF OF PROPOSITION 3. Given a wide-gap situation, from Proposition 1 if countries are of equal size, then the less-developed country will grow faster by opening trade (i.e., $dT^A/dt < dT^B/dt$). Figure 3 shows that as the gap narrows, the growth rate in country B continuously declines. Thus, the difference between growth rates in the two countries (g^A and $g^{B'}$ in Figure 3) will contract. Under the narrow-gap situation when two countries' technology levels are close together and upon opening trade, country A will actually take the advantage and grow faster as depicted in equations (18) and (19) (i.e., $dT^A/dt > dT^B/dt$). Hence, the technology gap between the two countries will widen, and the difference between growth rates in the two countries will continuously shrink as shown in Figure 3. Therefore, there exists a persistent gap ($T^A - T^B$), such that $dT^A/dt = dT^B/dt$. Since given a technology gap the growth rate in country B is greater with technology spillover than without, the persistent gap will be smaller and the corresponding growth rates of the two countries will be greater with technology spillover than without (i.e., $G' < G$ and $g^{**} > g^*$ as shown in Figure 3). Q.E.D.

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