Price-Channel Effects of North-South Trade on the Direction of Technological Knowledge and Wage Inequality

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Abstract

This paper develops a general equilibrium endogenous growth model that emphasizes the mechanisms, other than market size, through which trade-induced North-South technological knowledge diffusion influences the direction of technological progress and, thus, the path of intra and inter-country wage inequality. In contrast with the market-size effect, more common in previous literature on skill-biased technological change, the operation of the price channel, central to this paper, predicts an increasing high-skilled technological bias following openness, which is more in line with the recent trends in developed and developing countries.

Keywords: North-South trade; Technological knowledge diffusion; Direction of technological progress; Wage inequality.

JEL classification Codes: F16, F43, O31, O33.

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1 Introduction

This paper aims at improving our understanding of how North-South diffusion of technological knowledge, through international trade, influences the direction of technological knowledge and wage inequality. We develop a dynamic general equilibrium model of endogenous growth, following and contributing to two main lines of research previously explored, notably, by: (i) technological-knowledge diffusion growth models of Grossman and Helpman (1991a, chs. 11-12) and Barro and Sala-i-Martin (1997); and (ii) direction of technological change and wage inequality growth models of Acemoglu and Zilibotti (2001) and Acemoglu (2002).

Recent interpretations of trends in intra-country wage inequality provide the main motivation for this research. Richardson (1995), among others, emphasizes two major trends, since the early 1980s, regarding low *versus* high-skilled wage inequality in developed and (newly-industrialized) developing countries: rise in wage inequality in favor of high-skilled labor; and rise in the proportion of high-skilled labor. These trends are concomitant with strong technological progress and enlarged trade flows between those countries.

Analyzing recent literature, one concludes that each major explanation explored to date contradicts at least one of these observed trends. Following Wood (1998), the mechanisms behind these explanations are grouped in two categories: technology and trade.

According to the technology approach, prominently explored by Acemoglu (*e.g.*, 1998 and 2002), the direction of technological change and the resulting path of the wage premium are driven by the rise in high-skilled labor supply. Thus, this explanation emphasizes the market-size effect on technological progress; but the operation of this very same effect with trade openness partially contradicts the argument – with an increase in trade between a high-skilled abundant country and a less-skilled one, the market-size channel would predict a reduction in the high-skilled technological bias.

As to the trade mechanism, adopted, *e.g.,* by Leamer (1996) and Wood (1998), the explanation relies mainly on the application of the Stolper-Samuelson theorem: imports of goods produced by less-skilled labor reduce less-skilled wages in the high-skilled abundant country. However, the same argument applied to the exporter-country would predict a rise in the less-skilled wage premium, which contradicts the trend in developing countries.

Both sides of this debate have been, in fact, dominated by labor endowments, either in a Heckscher-Ohlian way or through R&D intensity. In the latter case a larger high-skilled labor endowment, for example, creates a larger demand for R&D directed towards improvements in inputs used in goods produced by high-skilled labor, thus increasing relative high-skilled wages. However, in addition to this market-size channel, the direction of R&D is also influenced by the price of goods - price channel -, since more expensive goods command higher profits for the producers of the respective inputs. For instance, the relative abundance of high-skilled labor increases the competitive price of goods produced by low-skilled workers and, thus, the demand for R&D directed towards improvements in goods produced by low-skilled labor. Pursuing this argument, when the high-skilled labor abundant country A exports inputs incorporating its R&D results to a low-skilled abundant country B, it benefits from the higher prices of goods produced by high-skilled workers in country B. The resulting profit opportunities redirect R&D towards inputs that increase the marginal productivity, and thus wages, of high-skilled labor.

By shifting to the price channel (instead of the market size) and by accounting for technological-knowledge diffusion, which we deem as non-dissociable from trade, we propose a framework capable of generating predictions compatible with the trend, described above, of wage inequality in developed and developing countries. Apart from the endogenous growth debate on scale effects (see, *e.g.*, Jones, 1995a, b; Dinopoulos and Thompson, 1998; and Howitt, 1999) our removal of the market-size channel is mainly an instrument to isolate the price mechanisms of technological-knowledge diffusion through international trade.

Our stylized North (developed) and South (developing) countries differ in levels of productivity, labor endowments and R&D capacity. These differences are assumed to have historical roots that are reflected in current institutional characteristics. Our main concern is not to explain these differences, but rather to take them as given at time zero and analyze the subsequent path of both economies under international trade. The North is more productive than the South due to domestic institutions, is endowed with a higher initial level of the more productive labor, and its R&D activities result in innovations that improve the quality of products – Schumpeterian R&D, as formalized by Aghion and Howitt (1992). The South has a marginal cost advantage in the production of final goods, and also conducts R&D, but its best results are imitations of the North's innovations – as in Grossman and Helpman (1991, chs. 11 and 12). Since we want to focus on technological diffusion through trade of intermediate goods, it is reasonable to consider that the South is not too backward relative to the developed North. The degree of backwardness is included by making the South's imitation of existing technology conditional to the distance to the technological frontier, in the sense that there is a threshold distance beyond which the cost of imitation is higher than the cost of re-inventing older product qualities.

Additional features of our model relate the technology of production, in both the North and South, to the structure of international trade. Each economy produces final goods with labor and intermediate goods, where R&D is directly applied. We focus on international trade of intermediate goods, since it is most relevant for technological-knowledge diffusion. As for the production of (non-traded) final goods, the crucial feature is the concurrence of complementarity in the use of inputs and substitutability between types of technology, following Acemoglu and Zilibotti (2001).

After these introductory remarks, the paper proceeds to characterize the North and South economies in section 2. Then, in section 3, international trade in intermediate goods is introduced and its level, steady-state and transitional dynamics effects derived. Section 4 concludes the paper with an assessment of the current state of this research.

2 Modeling the domestic economy

We characterize the North economy and, in the process, highlight the differences with the South. The economy is composed of two sectors: producers of final goods and producers of intermediate goods. The R&D activities are directly connected to the intermediate-goods sector, where competitive monopolists use the innovative blueprints as inputs, as in Romer (1990).

2.1 Final-goods technology

Final goods – Y, continuously indexed by $n \in [0, 1]$ – are produced in perfect competition. Following the Schumpeterian set-up[1] complemented with the recent contribution of Acemoglu and Zilibotti (2001), we consider that each final good is producible by two technologies, Low and High. The Low-technology uses low-skilled labor, L, complemented with a continuum of Low-specific intermediate goods indexed by $j \in [0, J]$. The High-technology's inputs are high-skilled

[1] As amply divulged by the textbooks of Barro and Sala-i-Martin (2004) and Aghion and Howitt (1998).

labor, H, complemented with a continuum of High-specific intermediate goods indexed by $j \in [J, 1]$. That is, each set of intermediate goods complements either type of labor, but not both. In production function form at time t,

$$Y_n = A \left\{ \left[\int_0^J \left(\sum_{k=0}^{k(j,t)} q^k \; x_n(k,j,t) \right)^{1-\alpha} dj \right] \; [(1-n) \;\; L_n]^\alpha + \right. \\ \left. + \left[\int_J^1 \left(\sum_{k=0}^{k(j,t)} q^k \; x_n(k,j,t) \right)^{1-\alpha} dj \right] \; [n \; h \; H_n]^\alpha \right\} . \quad , \qquad (1)$$

The first and third expressions within square brackets sum up the contributions of the two types of intermediate goods to production, while the second and fourth represent the role of the specific labor inputs. Parameter $\alpha \in]0, 1[$ is the labor share in production. The term A is a positive exogenous variable representing the level of productivity, dependent on the country's domestic institutions (*i.e.*, non-international trade related), namely property rights, tax laws and government services. Indexing the South by S and the North by N, we consider $A_S < A_N$ as the only North-South difference in the parameters of the production function of final goods.

The labor terms include the quantities employed in the production of the n^{th} final good – L_n and H_n – and two types of corrective factors accounting for productivity differentials. An absolute productivity advantage of high-skilled over low-skilled labor is accounted for by the parameter h, assuming $h \geqslant 1$; *i.e.*, assuming a technological bias in favour of the High-technology. A relative productivity advantage of either type of labor is captured by the terms n and $(1-n)$. The use of these adjustment terms transforms the final-goods index n into a relevant ordering index: meaning that high-skilled labor is relatively more productive in producing final goods indexed by larger ns, and *vice-versa*. Since $n \in [0, 1]$, there is a threshold final good $\overline{n}$, endogenously determined, where the switch from one technology to another becomes advantageous, as will become clear below. In this sense, $\overline{n}$ defines the structure of final-goods production.

Each of the two intermediate-goods terms includes an adjustment for quality that reflects a stylized technological change process of the quality ladder type. The size of each quality upgrade obtained with each successful research is denoted by q, an exogenously determined constant greater than 1. The rungs of the quality ladder are indexed by k, with higher ks denoting higher quality. At time 0, the highest quality good in each intermediate-goods industry has a quality index $k = 0$. At time t the highest quality good produced by industry j has a quality index $k(j,t)$. The quantity $x_n(k,j,t)$ of the quality rung k of the intermediate good j is used, together with its specific labor, to produce $Y_n(t)$. Hence,

$$\sum_{k=0}^{k(j,t)} q^k \; x_n(k,j,t) \tag{2}$$

is the quality-adjusted total amount of the intermediate good j, and $(1-\alpha)$ is its share in the final-good production.

Because of profit maximizing limit pricing by the monopolist producers of intermediate goods, only the highest quality available of each intermediate good is actually used, so that the quality-adjusted amount (2) becomes

$$q^{k(j,t)} \; x_n(k,j,t). \tag{3}$$

Taking this into account, the zero profit equilibrium of the (constant returns to scale perfectly competitive) producers of final goods yields the demand for each intermediate good (highest quality only) by the representative producer of n^{th} final good,

$$x_n(k,j,t) = (1-n) \; L_n \; \left[\frac{p_n(t) \; A \; (1-\alpha)}{p(j,t)}\right]^{\frac{1}{\alpha}} \; q^{k(j,t)\left[\frac{1-\alpha}{\alpha}\right]}, \text{ if } 0 < j \leq J \; ; \tag{4a}$$

$$x_n(k,j,t) = n\ h\ H_n\ \left[\frac{p_n(t)\ A\ (1-\alpha)}{p(j,t)}\right]^{\frac{1}{\alpha}}\ q^{k(j,t)\left[\frac{1-\alpha}{\alpha}\right]},\ \text{if}\ J < j \leq 1, \tag{4b}$$

where $p_n(t)$ is the price of final good n, $p(j,t)$ is the price of intermediate good j, and the numeraire is the composite final good. All prices are given for the perfectly competitive producers of final goods.

Plugging equations (4a) and (4b) into the production function (1), and using only the highest quality of each intermediate good, the supply of final good n is

$$Y_n(t) = A^{\frac{1}{\alpha}} \left[\frac{p_n(t)\ (1-\alpha)}{p(j,t)}\right]^{\frac{1-\alpha}{\alpha}} \left[(1-n)\ L_n\ Q_L(t) + n\ h\ H_n\ Q_H(t)\right] \tag{5}$$

$$\text{where } Q_L(t) \equiv \int_0^J q^{k(j,t)\left[\frac{1-\alpha}{\alpha}\right]}\ dj \text{ and } Q_H(t) \equiv \int_J^1 q^{k(j,t)\left[\frac{1-\alpha}{\alpha}\right]}\ dj \tag{6}$$

are the aggregate domestic quality indexes, measuring domestic technological knowledge. The ratio $\frac{Q_H}{Q_L}$ is the relative productivity of the High technological knowledge, which is an appropriate measure of the technological-knowledge bias. Equation (5) clearly shows how growth of final production is driven by growth of technological knowledge.

The prices' numeraire – the composite final good – is defined by integration over final goods:

$$Y(t) = \int_0^1 p_n(t)\ Y_n(t)\ dn = \exp\left[\int_0^1 \ln Y_n(t)\ dn\right]\ . \tag{7}$$

2.2 Intermediate-goods technology

Since, by assumption, the production of intermediate goods and R&D are financed by the resources saved after consumption of the composite final good, the simplest hypothesis is to consider that the production function of intermediate goods is identical to the composite final good specified by equations (7) and (1).[2] Given this convenient simplification, the marginal cost, MC, of producing an intermediate good equals the MC of producing the composite final good, which, due to perfect competition in the final-goods sector, equals the price of the composite final good (numeraire); in short, $MC = 1$. Thus, the MC of producing an intermediate good is independent of its quality level and is identical across all domestic industries.

The manufacture of an intermediate good requires a start-up cost of R&D in a new design. This investment in a blueprint can only be recovered if profits are positive within a certain period in the future. This is guaranteed by domestically enforced patents – *i.e.*, there is a domestic system of intellectual property rights (IPRs) –, which protect the leader firm's domestic monopoly of that quality good, while at the same time disseminating acquired knowledge to other domestic firms. Under these assumptions, knowledge of how to produce a good is public (non-rival and non-excludable) within a country.

Maximization of profits, given demand equations (4a) or (4b), yields the mark-up price:

$$p(k, j, t) = p(j, t) = p = \frac{1}{1-\alpha}, \tag{8}$$

which is constant over time, across industries and for all quality grades. The closer α is to zero, the smaller the mark-up – *i.e.*, there is less room for monopoly pricing.

Since the last innovator in each industry is the only firm legally allowed to produce the highest quality intermediate good, it will use pricing to wipe out sales of lower quality intermediate goods in its industry. Depending on whether $q(1-\alpha)$ is greater or less than $MC = 1$, the leader of each industry will,

[2] Or, equivalently, that the composite final good is the input in the production of each intermediate good, as in Barro and Sala-i-Martin (1997), for example.

respectively, use the monopoly pricing (8) or the limit pricing

$$p = q \tag{9}$$

to capture the entire market (see, for example, Barro and Sala-i-Martin, 2004, ch. 7). We assume, for example like Grossman and Helpman (1991a, ch. 4), that limit pricing is binding.[3]

Since the lowest price that the closest follower can charge without negative profits is MC, the leader can successfully capture the entire market by selling at a price slightly below qMC, because q is the quality advantage over the closest follower. Therefore, the size of each quality improvement is also an indicator of the market power of the incumbent firm in each intermediate-goods industry.

2.3 Equilibrium for given technological knowledge

It is now convenient to derive the domestic equilibrium of the economy, for given technological knowledge defined by (6). Then, the description of R&D activity closes the model of the domestic economy.

An important feature of the equilibrium is that only one technology, Low or High – *i.e.*, one combination of intermediate goods of a certain type and the respective labor – is used to produce a particular final good. The derivation of this result follows, with the due differences, Acemoglu and Zilibotti (2001).

The pattern of relative advantage embedded in the production function (1) through the adjustment terms n and $(1-n)$ makes H relatively more productive in high index final goods. Together with profit maximization, this pattern implies the existence of a threshold final good $\overline{n} \in [0,1]$ such that only Low-technology is used to produce final goods indexed by $n \leq \overline{n}$, and only High-

[3] In other words, we assume that quality improvements q are not large enough ($q \leq \frac{1}{1-\alpha}$), to enable each leader to use monopoly pricing.

technology is used to produce goods with $n > \overline{n}$; *i.e.*, in production function (1),

$$\begin{aligned} H_n(t) &= x_n(k,j,t) = 0, \text{ where } J < j \leq 1, \ \forall\ 0 \leq n \leq \overline{n} \\ L_n(t) &= x_n(k,j,t) = 0, \text{ where } 0 \leq j \leq J, \ \forall\ \overline{n} \leq n \leq 1 \end{aligned} . \tag{10}$$

The determination of $\overline{n}$ follows from equilibrium in the factors markets, by equalizing the marginal value product of each type of labor across the relevant final-goods industries – $n \leq \overline{n}$ for L and $n > \overline{n}$ for H. The resulting $\overline{n}$, as a function of the currently given variables, is

$$\overline{n}(t) = \left\{ 1 + \left[\frac{Q_H(t)\ h\ H}{Q_L(t)\ L} \right]^{\frac{1}{2}} \right\}^{-1}, \tag{11}$$

where H and L are the exogenous levels of each type of labor, assumed to be fully employed at each point in time.

It is useful to relate $\overline{n}$ to prices, as well. This is achieved by taking into account that in the production of the threshold final good $n = \overline{n}$ both a firm that uses Low-technology and a firm that uses High-technology should break even. This turns out to yield, at each moment in time, the following ratio of index prices of goods produced with High and Low technologies:

$$\frac{p_H}{p_L} = \left(\frac{\overline{n}}{1 - \overline{n}} \right)^{\alpha}, \tag{12}$$

where prices are, at each period t, conveniently indexed as

$$p_n = \begin{cases} p_L\ (1 - \overline{n})^{-\alpha}, & \forall\ 0 \leq n \leq \overline{n} \\ p_H\ \overline{n}^{-\alpha}, & \forall\ \overline{n} \leq n \leq 1 \end{cases}. \tag{13}$$

Equation (11) shows that either if technological knowledge is highly biased – that is, high $\frac{Q_H}{Q_L}$ – or if there is a large relative supply of H, the fraction of industries using the High-technology is large and so $\overline{n}$ is small. In terms of prices, small $\overline{n}$ implies that the relative price of High-technology goods is also low and, conversely, the relative price of Low-technology goods is high, as equation (12) shows. In this situation, the demand for Low-specific intermediate goods is high – equations (4a) and (4b) –, increasing the demand for Low-specific new designs and inducing R&D activities aimed at improving Low-specific technologies. In sum, the structure of labor endowments influences the direction of R&D through the price (of final goods) channel – *i.e.*, there are stronger incentives to develop technologies when the final goods produced by these technologies command higher prices.[4]

The equilibrium aggregate output at each time t – the composite final good from equation (7) – is expressible as a function of the currently given aggregate domestic quality indexes,

$$Y(t) = \exp(-1)\ A^{\frac{1}{\alpha}} \left(\frac{1-\alpha}{q}\right)^{\frac{1-\alpha}{\alpha}} \left\{[L\ Q_L(t)]^{\frac{1}{2}} + [h\ H\ Q_H(t)]^{\frac{1}{2}}\right\}^2. \tag{14}$$

Since $w_m(t)$ – the wage per unit of m-type labor, where $m = H, L$ – is equal to its marginal product, the high-skilled labor premium (intra-country wage inequality measure) is

$$\frac{w_H(t)}{w_L(t)} = \left[\frac{Q_H(t)\ h}{Q_L(t)}\right]^{\frac{1}{2}} \left(\frac{H}{L}\right)^{-\frac{1}{2}}, \tag{15}$$

and the relative (to the North) high and low-skilled wages in the South (reflecting inter-country wage inequality) become, respectively,

$$\frac{w_{H,S}(t)}{w_{H,N}(t)} = \left[\frac{p_{H,S}(t)\ A_S}{p_{H,N}(t)\ A_N}\right]^{\frac{1}{\alpha}} \frac{Q_{H,S}(t)}{Q_{H,N}(t)}; \tag{16a}$$

[4] This price channel shows up in various papers by Acemoglu (*e.g.*, 2002), although always dominated by the market-size effect, which, in our case, is removed – see below the equilibrium R&D in section 3.

$$\frac{w_{L,S}(t)}{w_{L,N}(t)} = \left[\frac{p_{L,S}(t)\ A_S}{p_{L,N}(t)\ A_N}\right]^{\frac{1}{\alpha}} \ \frac{Q_{L,S}(t)}{Q_{L,N}(t)}. \tag{16b}$$

Since we are considering that the South is not too backward, it is predictable that inter-country differences in prices of final goods are of second order.[5] Bearing this in mind, inspection of equations (16a) and (16b) shows that wages are higher in the North, as a result of absolute advantage in exogenous productivity – $A_N > A_S$ – and in domestic technological knowledge – $Q_{H,N} > Q_{H,S}$ and $Q_{L,N} > Q_{L,S}$.

2.4 Consumers

A time-invariant number of heterogeneous individuals – continuously indexed by $i \in [0,1]$ – decide the allocation of income, which is partly spent on consumption of the composite final good, and partly lent in return for future interest. For simplicity, we consider an exogenous threshold individual $\bar{i}$, such that individuals $i > \bar{i}$ are high-skilled workers, whereas individuals $i \leq \bar{i}$ are low-skilled workers.

With a constant intertemporal elasticity of substitution (CIES) instantaneous utility function, the infinite horizon lifetime utility of an individual i is

$$U(i,t) \equiv \int_0^\infty \left[\frac{c(i,t)^{1-\theta} - 1}{1-\theta}\right] \exp(-\rho t)\ dt \tag{17}$$

where $c(i,t)$ is individual consumption at time t, $\rho > 0$ is the homogeneous subjective discount rate and $\theta > 0$ is the constant elasticity of marginal utility with respect to consumption.

The budget constraint of individual i equalizes income earned to consumption plus savings, at each t. Savings consists of accumulation of financial assets – K, with return r – in the form of ownership of the firms that produce inter-

[5] Inter-country differences in prices of final goods depend on differences in the structure of final goods production (*i.e.*, in the threshold final good $\overline{n}$) and of labor endowments.

mediate goods in monopolistic competition. The value of these firms, in turn, corresponds to the value of patents in use. The budget constraint, expressed as savings = income - consumption, is

$$\dot{K}(i,t) = r(t)\ K(i,t) + w_m\ m(i) - c(i,t), \tag{18}$$

where $m = \begin{cases} H, & \text{if } i > \bar{i} \\ L, & \text{if } i \leq \bar{i} \end{cases}$ indexes the type of labor specific to the individual.

Each individual maximizes lifetime utility (17), subject to the budget constraint (18). The solution for the consumption path, which is independent of the individual, is the standard Euler equation

$$\widehat{c}(t) = \frac{1}{\theta}\left[r(t) - \rho\right], \tag{19}$$

where $\widehat{c}$ is the growth rate of c.

2.5 R&D technology

R&D drives the North and South economic growth. A more detailed description of the technology of R&D activities is thus in order, closing the characterization of the North and South domestic economies.

The R&D activities in the North result in innovative designs for the manufacture of intermediate goods, which increase their quality. The designs are domestically patented and the leader firm in each intermediate-goods industry – the one that produces according to the latest patent – uses limit pricing (9) to assure monopoly. The value of the leading-edge patent depends on the profit-yields accruing during each period t to the monopolist, and on the duration of the monopoly power. The duration, in turn, depends on the probability of a new innovation, which creatively destroys the current leading-edge design – in the lines of the Schumpeterian models introduced by Segerstrom *et al.* (1990) and Aghion and Howitt (1992). The probability of a successful innovation is, thus, at the heart of R&D.

Let $pb_N(k, j, t)$ denote the instantaneous probability at time t – a Poisson arrival rate – of Northern successful innovation in the next higher quality $[k(j, t) + 1]$ in intermediate-goods industry j,

$$pb_N(j,t) = y_N(j,t) \cdot \beta_N \; q^{k(j,t)} \cdot \zeta_N^{-1} \; q^{-\alpha^{-1} k(j,t)} \cdot m_N^{-\xi_N}, \qquad (20)$$

where:

(i) $y_N(j, t)$ is the flow of domestic final-good resources devoted to R&D in intermediate good j, which defines our framework as a lab equipment model – *e.g.*, Rivera-Batiz and Romer (1991);

(ii) $\beta_N \; q^{k(j,t)}$, $\beta_N > 0$, represents learning by past domestic R&D, as a positive learning effect of accumulated public knowledge from past successful R&D – *e.g.*, Grossman and Helpman (1991, ch. 12) and Connolly (2003);

(iii) $\zeta_N^{-1} \; q^{-\alpha^{-1} k(j,t)}$, $\zeta_N > 0$, is the adverse effect – cost of complexity – caused by the increasing complexity of quality improvements – *e.g.*, Kortum (1997) and Dinopoulos and Segerstrom (2004);[6]

(iv) $m_N^{-\xi_N}$, $m_N = L_N$ when $0 \leq j \leq J$ and $m_N = H_N$ when $J < j \leq 1$, $\xi_N > 0$, is the adverse effect of market size, capturing the idea that the difficulty of introducing new quality intermediate goods and replacing old ones is proportional to the size of the market measured by the respective labor. That is, for reasons of simplicity, we reflect in R&D the costs of scale increasing, due to coordination among agents, processing of ideas, informational, organizational,

[6] This complexity cost is modelled in such a way that, together with the positive learning effect (ii), exactly offsets the positive influence of the quality rung on the profits of each leader intermediate good firm – calculated below; this is the technical reason for the presence of the production function parameter α in the expression – see also Barro and Sala-i-Martin (2004, ch. 7).

marketing and transportation costs, as reported by works such as Becker and Murphy (1992), Alesina and Spolaore (1997), Dinopoulos and Segerstrom (1999) and Dinopoulos and Thompson (1999).[7]

In the absence of international trade, the South mimics the R&D process of the North, but less efficiently, *i.e.*, with $k_S \leq k$ in expression (20). Since the South is less developed, but not too backward, we assume that there are some intermediate goods j, but not all, for which $k_S < k$, implying that even in the absence of trade there are some state-of-the-art intermediate goods produced in both countries (*i.e.*, for which $k_S = k$).

Once the South has access to all the best quality intermediate goods through international trade, it becomes an imitator, improving the probability of successful R&D. Hence, the South's R&D activities, when successful, result in imitation of current worldwide best qualities. Denoting the probability of successful imitation by $pb_S(k, j, t)$ – the instantaneous probability of successful imitation of the current higher quality $k(j, t)$ in intermediate-goods industry j,

$$pb_S(k,j,t) = \begin{array}{c} y_S(j,t) \cdot \beta_S \; q^{k_S(j,t)} \cdot \zeta_S^{-1} \; q^{-\alpha^{-1} k(j,t)} \cdot m_S^{-\xi_S} \cdot \\ \cdot B_D(j,t) \cdot B_T(j,t) \cdot f(\widetilde{Q}_m(t), d)^{-\sigma + \widetilde{Q}_m(t)} \end{array}, \tag{21}$$

where:

(i) $y_S(j, t)$ is the flow of domestic final-good resources devoted to R&D in intermediate good j;

(ii) $\beta_S \; q^{k_S(j,t)}$, $0 < \beta_S < \beta_N$, $k_S \leq k$; *i.e.*, we consider that the learning by past imitations is lower that the learning by past innovations;

(iii) $\zeta_S^{-1} \; q^{-\alpha^{-1} k(j,t)}$, $\zeta_N > \zeta_S > 0$; *i.e.*, we assume that the complexity cost of imitation is lower than the innovation's, in line with Mansfield *et al.* (1981) and Teece (1977);

[7] Dinopoulos and Thompson (1999), in particular, provided micro foundations for this effect in a model of growth through variety accumulation.

(iv) $m_S^{-\xi_S}$, $m_S = L_S$ when $0 \leq j \leq J$ and $m_S = H_S$ when $J < j \leq 1$, $\xi_S > 0$, is the adverse effect of market size;

(v) $B_T(j,t) \cdot B_D(j,t) \cdot f(\widetilde{Q}_m(t), d)^{-\sigma + \widetilde{Q}_m(t)}$, $0 < \widetilde{Q}_m(t) < 1$, $\overline{\sigma} > 0$. This is a catching-up term, specific to the South, which sums up positive effects of imitation capacity and backwardness.

Further remarks on each term of the catching-up factor (21)-(v) are in order.

Terms $B_D(j,t)$ and $B_T(j,t)$ are positive exogenous variables, which capture important determinants of imitation capacity. The former represents the level of imitation productivity dependent on domestic causes, which includes domestic policies promoting R&D – *e.g.*, Aghion *et al.* (2001, 2004). The latter embodies the level of imitation productivity dependent on external causes, and thus comprises the degree of openness to international trade – *e.g.*, Coe and Helpman (1995) and Coe *et al.* (1997) – and other trade policies, namely international integration – *e.g.*, Grossman and Helpman (1991, ch, 11), as well as the South's relative level of labor. Therefore, we assume that labor enhances the imitation capacity, thereby speeding up convergence with the North – as argued by Nelson and Phelps (1966) and, more recently, by Benhabib and Spiegel (1994) and Aghion *et al.* (2004), among others.

In order to capture the benefits of relative backwardness, function $f(\widetilde{Q}_m(t), d)$ – similar to Papageorgiou (2002) – is

$$f(\widetilde{Q}_m(t), d) = \begin{cases} 0 & , \text{if } 0 < \widetilde{Q}_m(t) \leq d \\ -\widetilde{Q}_m(t)^2 + (1+d)\ \widetilde{Q}_m(t) - d & , \text{if } d < \widetilde{Q}_m(t) < 1 \end{cases} , \quad (22)$$

where $\widetilde{Q}_m(t) \equiv \frac{Q_{m,S}(t)}{Q_{m,N}(t)}$ is the relative technological knowledge level of the South's m-specific intermediate goods.[8]

[8] Thus, we assume that the probability of successful imitation in intermediate good j is state dependent on all past successful research in all intermediate goods of its type in both countries, contrary to the probability of successful innovation, which is state dependent only on the stock of past successful research in intermediate good j in the North.

Provided that the gap is not large – *i.e.*, if $\widetilde{Q}_m(t)$ is above threshold d – then the country can benefit from an advantage of backwardness, as in Barro and Sala-i-Martin (1997). When the gap is wider – so that $\widetilde{Q}_m(t)$ is below threshold d – backwardness is no longer an advantage (in line with Verspagen, 1993, for example).

Function $f(\widetilde{Q}_m(t), d)$ is quadratic over the range of main interest, and, once affected by the exponent function $(-\sigma + \widetilde{Q}_m)$ in (21)-(v), yields an increasing (in the technological knowledge gap) advantage of backwardness – where the size of σ affects how quickly the probability of successful imitation falls as the technological knowledge gap falls.

3 Technological knowledge dynamics with North-South trade in intermediate goods

With the countries' structure characterized, we now proceed to consider international trade of intermediate goods. In this context, the South has access to the same technological knowledge as the North, either by imitation of the latest innovations, or by importing state-of-the-art intermediate goods.[9] This improvement in the level of technological knowledge available to the South is a static benefit of international trade, with immediate effects on the levels of productivity and prices of goods and factors. The dynamics – growth effect – involves the South as well as the North, due to interaction (feedback) between the countries.

Assuming balanced trade without international mobility of the other factors of production and assets, the South, in order to import some intermediate

[9] However, Southern technological knowledge, $Q_{m,S}$, is not equalized with the North because at each point in time not all innovations have been imitated yet. Hence, it is useful to keep in mind the distinction between (i) Southern technological knowledge and (ii) available technological knowledge in the South, $Q_{m,N}$.

goods, has to be able to export other intermediate goods. Due to marginal cost advantages, the intermediate goods of which top-qualities are imitated become South's exports.

3.1 Worldwide limit pricing, intermediate-goods demand and final-goods supply

We must distinguish now between the composite final good of the North defined by (7) and the Southern one, which is also defined by integration over final goods and which we assume is produced at a lower marginal cost, MC_S. Since under perfect competition prices equal marginal costs, the South's aggregation of final goods is

$$Y_S(t) = MC_S \; \exp\left[\int_0^1 \ln Y_n(t) \; dn\right] \; . \tag{23}$$

where $0 < MC_S < MC_N = 1$ (recall the intermediate-goods technology in section 2 above).

Due to the simplification in technology explained in section 2, this marginal cost advantage is transmitted to the production of intermediate goods. This influences worldwide optimizing limit pricing by the relevant competitive monopolists – *e.g.*, Grossman and Helpman (1991, ch. 12). The three possible sequences of successful R&D outcomes and their limit pricing consequences at time t, given quality k at time $t - dt$, are depicted in table 1.

The first mark-up is the one in equation (9) and is the highest – the Northern entrant (N) competes with a Northern incumbent (N) at the same marginal cost but with better quality. The second one is smaller – the Southern entrant (S), with lower marginal cost, competes in the same quality rung with a Northern incumbent (N). Compared with the first, the third mark-up is again smaller,

$t-dt$	t	Share in intermediate goods production at t	$p(j)$
N produces and exports quality k	N produces and exports quality $k+1$	$\Phi_m\ (1-\Psi_m)$	$p_{m,N-N}(j)=q$
N produces and exports quality k	S produces and exports quality k	$1-\Phi_m$	$p_{m,S-N}(j)=1$
S produces and exports quality k	N produces and exports quality $k+1$	$\Phi_m\ \Psi_m$	$p_{m,N-S}(j)=q\ MC_S$

Table 1: Limit pricing of each intermediate good

but due to a different reason – the Northern entrant improves quality as in the first case, but competes with an incumbent with lower marginal cost.

In order to pin down which intermediate goods are produced in each country at each moment in time, let

(i) Φ_m and $(1-\Phi_m)$ be the proportion of intermediate goods of m-type with production in the North and in the South, respectively;

(ii) Ψ_m be the proportion of intermediate goods of m-type produced in the North having overcome imitator competition;

(iii) $(1-\Psi_m)$ be the proportion of intermediate goods of m-type produced in the North having overcome innovator competition.[10]

We can now define a price index for the m-type intermediate goods – at each moment in time – as a weighted average of the limit prices in table 1,

$$\overline{p}_m = 1 + \Phi_m\,[q-1] - \Phi_m\ \Psi_m\ q\ (1-MC_P). \tag{24}$$

[10] The specification of these proportions as functions of the probabilities of successful R&D, necessary for transitional dynamics, has been carried out (but not presented here) in such a way that, as in Dinopoulos and Segerstrom (2004), the proportion of intermediate goods produced in the North increases with the probability of innovation and decreases with the probability of imitation.

3.2 Level effects in the South

The static effect of international trade influencing the South is apparent in the equilibrium threshold final good

$$\overline{n}_S(t) = \left\{ 1 + \left[\frac{Q_{H,N}(t)\ h\ H_S}{Q_{L,N}(t)\ L_S} \right]^{\frac{1}{2}} \right\}^{-1}. \tag{25}$$

By allowing international access to the state-of-the-art intermediate goods, international trade affects the structure of final-goods production in the South – through the ratio $\frac{Q_{H,N}}{Q_{L,N}}$. Since the technological knowledge gap is always favorable to the North in either specific knowledge – *i.e.*, $Q_{m,N} > Q_{m,S}$ –, the South enjoys an immediate absolute and relative (to the North) benefit in terms of aggregate product and factor prices. That is apparent in equations (14), (16a) and (16b) above, provided that the changes in mark-ups are of second order. In fact, both the level of the composite final good and the marginal productivity of H and L increase with $Q_{m,N}$.

Assuming that endowments of labor are such that the North is relatively H abundant, *i.e.*,

$$\frac{H_N}{L_N} > \frac{H_S}{L_S}, \tag{26}$$

comparison of (25) with the respective expression for the North – from (11) – shows that $\overline{n}_S > \overline{n}_N$. Since Northern and Southern producers have access to the same state-of-the-art intermediate goods, differences in the structure of final-goods production is determined exclusively by differences in domestic labor endowments, which imply that, under international trade, the North produces more High-technology final goods than the South.

Notice that, through the operation of the price channel, the $\overline{n}_S$ given by (25) is larger than in pre-trade. This is because, as discussed in 2.3 above, labor endowments influence the direction of R&D in such a way that there are stronger incentives to improve technological knowledge that saves the relatively scarce type of labor. Since the South is H scarce, its pre-trade technological-knowledge bias is $\frac{Q_{H,S}}{Q_{L,S}} > \frac{Q_{H,N}}{Q_{L,N}}$.[11]

Concerning the level effect on wages, inter-country wage inequality (16a and 16b) falls because the technological knowledge progress embodied in internationally traded intermediate goods is the same for both countries.[12] The access to more productive intermediate goods shifts upwards the demand for both types of labor in the South. The resulting absolute (and relative to the North) benefit to both types of Southern labor is not balanced though. Indeed, the level effect reduces intra-South wage inequality (high-skilled labor premium), as shown by plugging the technological-knowledge bias implied by the assumed relative labor endowments into equation (15),

$$\frac{w_{H,S}}{w_{L,S}} = \left[\frac{Q_{H,N}}{Q_{L,N}}h\right]^{\frac{1}{2}} \left(\frac{H_S}{L_S}\right)^{-\frac{1}{2}} < \left.\frac{w_{H,S}}{w_{L,S}}\right|_{pre-trade} = \left[\frac{Q_{H,S}}{Q_{L,S}}h\right]^{\frac{1}{2}} \left(\frac{H_S}{L_S}\right)^{-\frac{1}{2}}. \tag{27}$$

In other words, the shift in the demand for L is more pronounced due to complementarity between intermediate goods and labor, together with the Northern technological-knowledge bias. This is a typical Stolper-Samuelson effect, with the relative wage of the relatively scarce factor (H, in the South) suffering with international trade.

The level effect of international trade also involves immediate changes in the allocation of resources. In particular, the amount of Southern resources devoted to R&D increases for two reasons. On the one hand, incentives to imitation increase through the positive effect of openness on the probability of

[11] This is clearly in contrast with what would be predicted by the market-size channel, through which the opposite would occur.

[12] However, the level effect does not fully equalize wages between North and South, as long as international immobility of labor and differences in exogenous productivity and marginal costs remain in place.

successful imitation (21-v, above); and, on the other hand, access to enlarged markets requires more resources due to the adverse effect of market size on the probability of successful imitation (21-iv, above).[13]

3.3 Equilibrium R&D

Given the functional forms (20) and (21) of the probabilities of success in R&D, which depend on the resources – composite final goods – allocated to it, free-entry equilibrium is defined by the equality between expected revenue and resources spent. Taking, for example, the case of imitation, such equality takes the form

$$pb_S(k,j,t)\ V_S(k,j,t) = y_S(j,t) \tag{28}$$

where $V_S(k,j,t)$ is the expected current value of the flow of profits to the monopolist producer of intermediate good j, or, in other words, the market value of the patent.[14]

The expected flow of profits depends on the amount in each period, the interest rate, and the expected duration of the flow, which is the expected duration of the imitator's technological leadership. Such duration, in turn, depends on the probability of a successful innovation in the North, which is the potential challenger, as shown in the third case in table 1.[15] The expression for V_S is

$$V_S(k,j,t) = \frac{\Pi_S(k,j,t)}{r_S(t) + pb_N(k,j,t)} \tag{29}$$

The amount of profits – Π_S –, at time t, for the monopolist producer of

[13] Resources devoted to R&D immediately increase in the North as well, but only for the second reason, *i.e.*, the adverse effect of market size on the probability of successful innovation (20-iv). Northern resources are reallocated at the expense of current consumption, differently form the South – where consumption increases with the immediate increase in aggregate income.

[14] Still in other words, V is the value of the monopolist firm, owned by domestic consumers.

[15] In the case of the value of a patented innovation – V_N – the challenge comes from both a new Northern innovation and a Southern imitation – *i.e.*, the first and second cases in table 1.

intermediate good j, using an imitation of quality k, depends on the marginal cost, the mark-up, and the world demand for intermediate good j by the final-goods producers. Its expression, for a High-specific j and recalling that $S-N$ indexes the second sequence in table 1, is

$$\begin{aligned}\Pi_{H,S-N}(k,j,t) = h\ (1-\alpha)^{\alpha^{-1}}\ q^{k(j,t)\ (1-\alpha)\alpha^{-1}}\ (1-MC_S) \\ \left\{H_S\ \left[A_S\ p_{H,S}(t)\right]^{\alpha^{-1}} + H_N\ \left[A_N\ p_{H,N}(t)\right]^{\alpha^{-1}}\right\}\end{aligned}, \qquad (30)$$

Plugging equation (30) into (29) and then (29) and (21) with $\xi_S = 1$ into (28) and solving for pb_N, the equilibrium probability of a successful innovation in a High-specific intermediate good – given the interest rate and the price indexes of final goods – is

$$\begin{aligned}pb_{H,N}(t) = \beta_S\ \zeta_S^{-1}\ B_D\ B_T\ \ f(\widetilde{Q}_H(t),d)^{-\sigma+\widetilde{Q}_H(t)}\ \widetilde{Q}_H(t)\ h \\ (1-\alpha)^{\alpha^{-1}}\ (1-MC_S)\ D_H(t) - r_S(t),\ \forall k\end{aligned}; \qquad (31)$$

where:

$$D_H(t) = \frac{H_S}{H_S+H_N}\left[A_S\ p_{H,S}(t)\right]^{\alpha^{-1}} + \frac{H_N}{H_S+H_N}\left[A_N\ p_{H,N}(t)\right]^{\alpha^{-1}}$$

The equilibrium m-specific $pb_{m,N}$ turns out to be independent of j and k. There are two reasons behind this independence. The first and most substantial one is the removal of scale of knowledge effects – the positive influence of the quality rung on profits and on the learning effect is exactly offset by its influence on the complexity cost – see the exponents of q in equation (30) and in equation (21)-(ii) and (iii). The second reason is the simplifying assumption that the determinants of imitation capacity, B_D and B_T in the catching-up term in equation (21)-(v), are not specific to each intermediate good.

Additional scale effects could arise through market size, as has been intensely discussed in the R&D endogenous growth literature since Jones' (1995) critique. Due to the technological complementarity in the production function (1), the size of the market for m-specific intermediate goods in our model is the m-type labor. Then, the scale effect is apparent in the size of the profits equation (30) – see the labor terms within square brackets. Since we aim at understanding international trade effects other than market size, the removal of scale is in order. The adverse effect of market size due to the scale-proportional difficulty of introducing new quality intermediate goods – term (iv) in equations (20) and (21) – is designed to offset the scale effect on profits. With $\xi = 1$, the offsetting is such that the influence of market size becomes negligible, as is apparent in expression D_H in equation (31).

Since the probability of successful innovation – as a Poisson arrival rate – determines the speed of technological knowledge progress, equilibrium can be translated into the path of Northern technological knowledge, from which free trade in intermediate goods allows the South to benefit as well. The relationship turns out to yield the following expression – where equation (31) is plugged in – for the equilibrium rate of growth of, for example, High-specific technological knowledge:

$$\widehat{Q}_{H,N}(t) = \begin{array}{l} \Big\{\beta_S \; \zeta_S^{-1} \; B_D \; B_T \; f(\widetilde{Q}_H(t), d)^{-\sigma + \widetilde{Q}_H(t)} \; \widetilde{Q}_H(t) \; h \\ \quad (1-\alpha)^{\alpha^{-1}} (1 - MC_S) \; D_H(t) - r_S(t)\Big\} \left[q^{(1-\alpha)\alpha^{-1}} - 1\right] \end{array} . \qquad (32)$$

It is clear in equation (32) that there are international trade feedback effects from imitation to innovation. That is, the positive level effect from the innovator to the imitator – the access to the state-of-the-art intermediate goods increases production and thus the resources available to imitation R&D – feeds back into the innovator, affecting the Northern technological knowledge through creative destruction.

Due to the technological complementarity in the production of final goods, the rate of growth of m-specific technological knowledge – equation (32) for the South and $m = H$ – translates into the growth of demand for m-type labor interrelated with the dynamics of the price indexes of final and intermediate goods ($p_{m,S}$ and $\overline{p}_m$, respectively), such that

$$\widehat{w}_{m,S}(t) = \frac{1}{\alpha}\,\widehat{p}_{m,S}(t) + \frac{\alpha-1}{\alpha}\,\widehat{\overline{p}}_m(t) + \widehat{Q}_{m,N}(t). \tag{33}$$

Thus, the path of m-wages in each country depends on the path of domestic demand for m-type labor, which, in turn, depends on the evolution of:

(i) the domestic range of the m-technology, established by threshold $\overline{n}$, which determines prices of (non-tradable) final goods;

(ii) the world demand for m-specific intermediate goods, reflected in international prices and driven by available technological knowledge.

3.4 Steady-state growth

Since, by assumption, both countries have the access – through free trade – to the same state-of-the-art intermediate goods and the same technology of production of final goods,[16] the steady-state growth rate must be the same as well. This implies, through the Euler equation (19), that interest rates are also equalized between countries in steady-state.

As for the sectorial growth rates, we note first that the instantaneous aggregate resources constraint – again in country S, for example – is

$$Y_S(t) = C_S(t) + X_S(t) + R_S(t), \tag{34}$$

where

[16] Except for the levels of exogenous productivity, A, and labor, m, in production function (1), which implies differences in the levels but not in the growth rates.

$Y_S(t)$ is total resources, the composite final good;

$C_S(t) = \int_0^1 c_S(i,t)di$ is aggregate consumption;

$X_S(t) = \int_0^1 \int_0^1 x_{n,S}(j,t)dndj$ is aggregate intermediate goods;

and $R_S(t) = \int_0^1 y_S(j,t)dj$ is total resources spent in R&D.

In other words, the aggregate final good is used for consumption and savings, which in turn are allocated between production of intermediate goods and R&D.[17] This implies that the steady-state growth rate of each of these variables is equal to the Northern growth rate of technological knowledge.

Since the composite final-good production is constant returns to scale in the inputs – see above equation (14) –, the constant, common to both countries, steady-state growth rate, designated by g^*, is

$$\widehat{Q}_H^* = \widehat{Q}_L^* = \widehat{Y}^* = \widehat{X}^* = \widehat{R}^* = \widehat{C}^* = \widehat{c}^* = \theta^{-1}(r^* - \rho) = g^*, \tag{35}$$

implying steady levels of threshold final goods, final and intermediate goods price indexes, wage premia, and gaps in both types of technological knowledge.[18] Although levels remain different (due to international immobility of labor and differences in exogenous productivity and marginal costs), steady-state growth of wages is equalized between countries, as derived by plugging in constant steady-state prices in (33), which is a Schumpeterian dynamic equivalent to the static factor-price equalization Samuelson's result.

Clearly, R&D drives steady-state endogenous growth. This feature is not, however, specific to international trade. In order to look at the steady-state effects of international trade we must investigate g^* further. To this end, we

[17] Net exports are always zero since, by assumption, trade is balanced.

[18] Indeed, while complete convergence in available technological knowledge is instantaneous with international trade (level effect), domestic levels may not converge completely, that is, $\tilde{Q}_H$ and $\tilde{Q}_L$ may remain below one.

compare the steady-state interest rate

$$r^* = \left\{ \left[q^{\left(\frac{1-\alpha}{\alpha}\right)} - 1 \right] \ \theta + 1 \right\}^{-1} \left\{ \beta_S \ \zeta_S^{-1} \ B_D \ B_T \ f(\widetilde{Q}_H^*, d)^{-\sigma + \widetilde{Q}_{H,}^*} \right. \\ \left. \widetilde{Q}_H^* \ h \ (1-\alpha)^{\alpha^{-1}} (1 - MC_S) \ D_H^* \ \left[q^{(1-\alpha)\alpha^{-1}} - 1 \right] \ \theta + \rho \right\} \quad ; \tag{36}$$

– obtained by setting the growth rate of consumption in (19) equal to the growth rate of Northern technological knowledge in (32) – with the one that would prevail in a pre-trade steady state.[19] Taking into account that goods, assets, as well as technological knowledge do not flow internationally in autarky, the advantage of backwardness and openness terms vanish from the probability of successful imitation (21). The increment in the steady-state interest rate, from autarky to trade in intermediate goods, depends on the difference

$$B_T \ f(\widetilde{Q}_H^*, d)^{-\sigma + \widetilde{Q}_{H,}^*} \ \widetilde{Q}_H^* \ (1 - MC_S) \ D_H^* - \\ - \left(\frac{q-1}{q}\right) \left[A_S \ \ p_{H,S}^* \big|_{pre-trade} \right]^{\alpha^{-1}} \ MC_S^{(\alpha-1)\alpha^{-1}} \quad . \tag{37}$$

While evaluation of equation (37) requires solving for transitional dynamics through calibration and simulation, we can, however, emphasize four ways, in addition to the level effects, through which international trade influences, in opposite directions, steady-state growth.

The first way in which international trade influences steady-state growth is the positive catching-up effect on the probability of successful imitation. Imitation capacity increases with the degree of openness, which is captured by B_T, and the advantages of backwardness are only obtained in the presence of international trade. Through the feedback effect described above, the probability of successful innovation, and thus the steady-state growth rate, are also affected – see equations (31) and (32).

The second way is the positive spillovers from North to South. Each inno-

[19] Then, g^* results from plugging the r^* into the Euler equation (19) or (35).

vation in the North tends to lower the cost of Southern imitation because the backwardness advantage is strengthened with each improvement of the technological knowledge frontier.

The third – counteracting – channel is the monopolistic competition mark-up. In (37) the Southern monopolist's mark-up under international trade is $(1 - MC_S)$, clearly less than the mark-up in the South under pre-trade, which is $(q - MC_S)$. This loss of profits also happens to the Northern monopolist: the average mark-up between the first and third situations in table 1 above is smaller than $(q - 1)$, which is the mark-up under pre-trade. The reason for this is that in pre-trade successful researches are protected from international competition. Once engaged in international trade and imitation becomes profitable (provided that the technological knowledge threshold d is overcome), profit margins in both North and South are reduced, which discourages R&D activities.[20]

The fourth – counteracting as well – way through which international trade influences steady-state growth, is that Southern firms have to support the R&D imitative cost of state-of-the-art intermediate goods, possibly several quality rungs above (and thus more complex) their own experience level in pre-trade. This is reflected in the presence of the technological knowledge ratio, $\widetilde{Q}_H^*$, in (37).

The effect of trade on the steady-state growth rate is, thus, ambiguous. However, the comparative statics (numerically computed based on the calibration in table 2, appendix) are not affected by such ambiguity because the reported changes in g^* (the first column of table 3, appendix) refer to steady-state growth under trade. This rate is affected by the levels of exogenous variables and parameters, which is to be expected in an endogenous growth model. In particular, both countries' exogenous levels of productivity (A_N and A_S) and parameters

[20] Contrary to previous models in which the reduction of margins is offset by market enlargement – *e.g.*, Rivera-Batiz and Romer (1991) –, we have removed the scale effect, as explained above.

of R&D technology (β, B_D and B_T) improve the common growth rate through their positive effect on the profibility of R&D, as (30) and (31) demonstrate. The impact on steady-state growth of the Southern marginal cost of final-goods production, MC_S, results from the combination of typical Schumpeterian-R&D effects: (i) by reducing productivity, it reduces resources available to R&D, and, consequently, both imitation and innovation (feedback effect); it also implies a smaller mark-up for the intermediate-goods producers in the South, thereby (ii) discouraging imitative R&D and (iii) encouraging innovative R&D; in our numerical calculations, the effects (i) and (ii) clearly dominate (iii).

3.5 Transitional dynamics and steady-state effects of trade

Numerical calculations describing dynamic equilibrium – which has involved parameter calibration and sensitivity analysis based on empirical literature and theoretical conditions, as presented in the appendix – confirms that optimal paths converge to the stable steady-state.

Moreover, the calculations uncover the price-channel effects of international trade on the dynamics of technological knowledge, relative prices and wages, assuming the starting condition stated in (26).

Technological-knowledge gap

While internationally available technological knowledge, $Q_{m,N}$, is the same in both countries, Southern technological knowledge, $Q_{m,S}$, remains lower because at each point in time, not all innovations have been imitated yet. The distance to the frontier of technological knowledge defines Southern backwardness – the converse of each ratio $\widetilde{Q}_m$. Figure 1 shows a reduction (after time zero, when a shift to free trade of intermediate goods occurs) of this distance in both types of technological knowledge during the transition to the steady state with international trade.[21]

Domestic accumulation of technological knowledge, through R&D, depends on the probability of success. Therefore, the reduction of the gaps must reflect differentiated changes in the probabilities of successful innovation and imitation. In addition to the advantage-of-backwardness effect on the probability of imitation, differentiated changes in the probabilities arise from inter-country differences in the allocation of resources to R&D. In fact, while increasing in both countries at rates higher than g^* during transition, R&D resources increase more in the South due to stronger incentives – reflected in higher interest rates. Incentives remain stronger in the catching-up South as long as the effect of the fall in the cost of imitation relative to innovation prevails, *i.e.*, during transition after opening to international trade.

Technological-knowledge bias and wage inequality

Figures 2 through 6 show transitional dynamics to steady states, triggered by North-South trade of intermediate goods that starts at time zero. The figures depict the paths of threshold final goods, relative prices of final goods, technological knowledge bias and wage inequality, and are arranged in a suitable order to accompany the sequence of analytical steps that follows.

Due to complementarity, the threshold final good, $\overline{n}$, and relative prices of High-technology final goods, $\frac{p_H}{p_L}$, are determined by the combination of the two types of technological knowledge with the respective labor – recall (11) and (12). Resulting from the steady-state relationships in (35) above, such a combination tends to a constant in each country and, consequently, so do $\overline{n}$ and $\frac{p_H}{p_L}$. As explained above in 3.2, the access to the Northern state-of-the-art intermediate goods, coupled with the relative scarcity of high-skilled labor in the South,

[21] Reduction of the gap occurs at decreasing rates because backwardness becomes less and less advantageous towards the steady state.

implies that relatively more Low-final goods are produced in the South (*i.e.* $\overline{n}_S > \overline{n}_N$), where, consequently, High-technology final goods are relatively more expensive – as results from (12).

Once international trade is introduced, both $\overline{n}$ and $\frac{p_H}{p_L}$ fall towards the steady-state. In fact, as the time zero (under trade) North-South average relative price of High-technology final goods is higher than the one prevailing in pre-trade North, the price channel – discussed above in 2.3 – enhances relative demand for High-specific new designs, biasing R&D in that direction, as shown in figure 4. Relative to pre-trade, such bias increases the world supply of High-specific intermediate goods, thereby increasing the number of High final goods and lowering their relative price in both countries.

Due to complementarity between inputs in the production of final goods, changes in intra-country wage inequality are closely related to the technological knowledge bias – as (15) clearly shows. The stimulus to the demand for H – arising from the technological bias induced by trade – increases the high-skilled labor premium in the North, relative to what would have prevailed under pre-trade (figure 5).

In pre-trade South, relative scarcity drives a higher H premium, which is reduced at time zero, as explained above in 3.2. This immediate effect in the level of the relative wage of H is partially reverted in the transition to the steady state – as figure 5 shows – due to the Northern technological knowledge bias, which, under trade, is embodied in the intermediate goods available to the South. Once in steady state, with a constant technological-knowledge bias implied by (35), intra-country wage inequality in both the North and South remains constant.

The wage-inequality paths in figure 5 are compatible with the trends (described by Richardson, 1995, for example) that point to an increase in wage inequality (in favor of high-skilled labor) in developed as well as in developing countries. In our model, such an increase is related to the bias in technological knowledge, which spreads from the more developed to the developing country through international trade. However, with fixed and immobile labor endowments, the Stolper-Samuelson trade level effect in the South, in favor of the relatively abundant less-skilled labor, dominates the subsequent dynamic path of increasing wage inequality.

In addition to the transition from pre-trade, analyzed above, the results of steady-state comparative statics under trade also reflect the mechanisms that closely connect the direction of technological knowledge with the path of intra-country wage inequality. Table 3 in the appendix shows partial derivatives (analytically or numerically computed) of the relevant variables with respect to exogenous variables, parameters and initial conditions, in steady-state with free trade of intermediate goods.[22]

The effects that exogenous changes have on technological-knowledge bias (column 2 in table 3) and on intra-country wage inequality (columns 3 and 4, table 3) are, thus, closely related. Take, for example, an increase in h, the absolute productivity advantage of high-skilled labor, which can be interpreted as the first stage of a new general purpose technology. The increase in h not only increases the high-skilled wage premium, but it also favors High-technology in the production of final goods (*i.e.*, the threshold final good, $\overline{n}$, falls). Consequently, relative demand for High-specific intermediate goods rises, enhancing, in turn, profits of High-specific R&D and thereby biasing technological knowledge in that direction.

In what respects the influence of initial relative levels on the steady state, table 3 shows that when the South is initially closer to the North in one type of technological knowledge – higher $\widetilde{Q}_H(0)$ or $\widetilde{Q}_L(0)$ – the steady-state technologi-

[22] Transitional dynamics is not shown, as its behavior is not qualitatively affected.

cal knowledge becomes more biased towards that type of knowledge, relative to the other. For example, figure 6 shows the stylized case of an increase in $\widetilde{Q}_H(0)$, which improves, at time zero and subsequently, the probability of successful innovation in High technological knowledge. The mechanism is the following: with larger domestic High technological knowledge, each High-Southern imitator faces less quality rungs to reach the state-of-the-art, thereby enhancing High-imitation, which, in turn, feeds back, under trade, into the North (as explained above in 3.3). Then, complementarity between inputs implies that the rising technological knowledge bias increases the high-skilled wage premium.

The effects of exogenous changes in labor endowments are straightforward. With scale effects removed, the technological-knowledge bias is not affected, and so an increase in the supply of one type of labor relative to the other simply diminishes its relative wage. If, for instance, the more productive labor becomes relatively more abundant in the North, then the wage premium of the less productive labor increases, as implied by (15). In our context of international immobility of labor, these changes do not extend to the South, and so inter-country wage inequality increases in favor of the North in low-skilled labor and in favor of the South in high-skilled labor (columns 5 and 6 of table 3).[23]

4 Concluding remarks

By considering international trade between North and South, two countries with different levels of development, but both capable of conducting R&D (innovative in the North and imitative in the South), this paper connects technological-knowledge diffusion with the direction of technological change and, thus, relates technological knowledge diffusion with the dynamics of inter and intra-country

[23] Table 3 shows that inter-country wage inequality is also straightforwardly affected by changes in a country's exogenous productivity, and by changes in marginal cost – an increase in the marginal cost in our lab-equipment model corresponds to an increase in wages.

wage inequality.

Our simulation results can be interpreted in comparison with previous literature about skill-biased technological change. In that literature, the bias that causes wage inequality is mainly induced through the market-size channel; whereas in our case, changes in the paths of inter and intra-country wage inequality result similarly from the direction of technological progress, but are, however, induced through the price channel under international trade. In contrast with the market-size channel, the operation of the price-channel yields an increase in the high-skilled technological bias following openness, which is more in line with the recent trends observed in developed and developing countries. With an extension of our model, allowing for simultaneous scale and price effects, future research should be able to assess the strength of the market-size *versus* price channels.

Further details of the dynamics of wage-inequality following trade provide another step for this research. Since in this paper, the relative-wage paths hinge, among other factors, on the assumption of fixed endowments, we intend to explore the effects of endogenous human capital accumulation

Finally, still another promising extension of the research follows from a recent characterization, by Aghion *et al.* (2003), of the explanations for rising wage inequality, stressing the importance of institutions. Our framework can accommodate the North-South spread of exogenous innovations of the general-purpose-technology type, which is interpretable and, thus, can be modelled as an institutional change.

Appendix: Baseline parameter calibration and comparative statics

Parameter calibration is based on empirical literature and theoretical conditions.

The final-goods technology parameter α has two interpretations in the model – the labor share in production, α, and the mark-up ratio, $\frac{1}{1-\alpha}$. Its value is set accordingly, in line with the mark-up estimates of Kwan and Lai (2003).

The baseline value for θ is in line with previous calibrations of growth models, where it is assumed to exceed one – *e.g.*, Jones *et al.* (1993). The annualized rate of time preference, ρ, also follows from previous works on growth – *e.g.*, Dinopoulos and Segerstrom (1999).

The other parameters have been calibrated taking into account our theoretical assumptions and considering a pre-trade Northern steady-state growth rate of 2%, which approximately matches the average per capita growth rate of the U.S. over the post-war period, as pointed out by Jones (1995b).

Parameter	Value
A_N	1.75
A_S	1.00
α	0.60
h	1.20
MC_S	0.60

Parameter	Value
β_N	1.60
β_S	1.00
ζ_N	4.00
ζ_S	2.50
B_D	1.28

Parameter	Value
B_T	1.85
σ	0.60
d	0.10
θ	1.05
ρ	0.03

Table 2: Baseline parameter values

	∂g^*	$\partial \frac{Q_{H,N}}{Q_{L,N}}$	$\partial \frac{w_{H,N}}{w_{L,N}}$	$\partial \frac{w_{H,S}}{w_{L,S}}$	$\partial \frac{w_{H,S}}{w_{H,N}}$	$\partial \frac{w_{L,S}}{w_{L,N}}$
∂A_N	$+$	≈ 0	≈ 0	≈ 0	$-$	$-$
∂A_S	$+$	≈ 0	≈ 0	≈ 0	$+$	$+$
∂h	$+$	$+$	$+$	$+$	≈ 0	≈ 0
∂MC_S	$-$	≈ 0	≈ 0	≈ 0	$+$	$+$
$\partial \beta_S$	$+$	≈ 0	≈ 0	≈ 0	≈ 0	≈ 0
$\partial \beta_N$	$+$	≈ 0	≈ 0	≈ 0	≈ 0	≈ 0
∂B_D	$+$	≈ 0	≈ 0	≈ 0	≈ 0	≈ 0
∂B_T	$+$	≈ 0	≈ 0	≈ 0	≈ 0	≈ 0
$\partial \frac{H_N}{L_N}$	≈ 0	≈ 0	$-$	≈ 0	$+$	$-$
$\partial \frac{H_S}{L_S}$	≈ 0	≈ 0	≈ 0	$-$	$-$	$+$
$\partial \widetilde{Q}_H(0)$	≈ 0	$+$	$+$	$+$	≈ 0	≈ 0
$\partial \widetilde{Q}_L(0)$	≈ 0	$-$	$-$	$-$	≈ 0	≈ 0

Note: ≈ 0 indicates a second-order negligible change

Table 3: Steady-state comparative statics under trade

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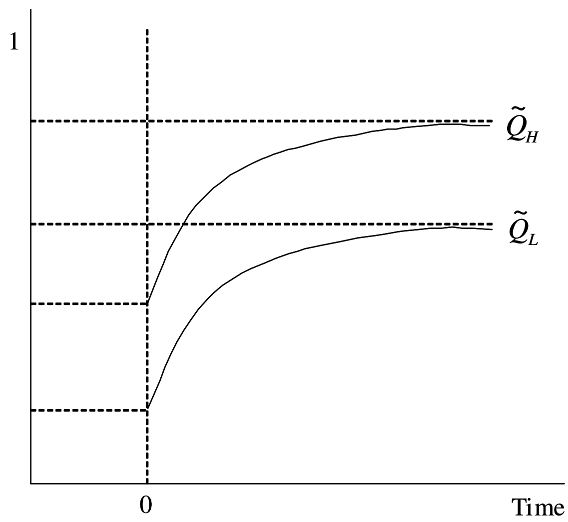

Figure 1: Inter-country technological knowledge ratios

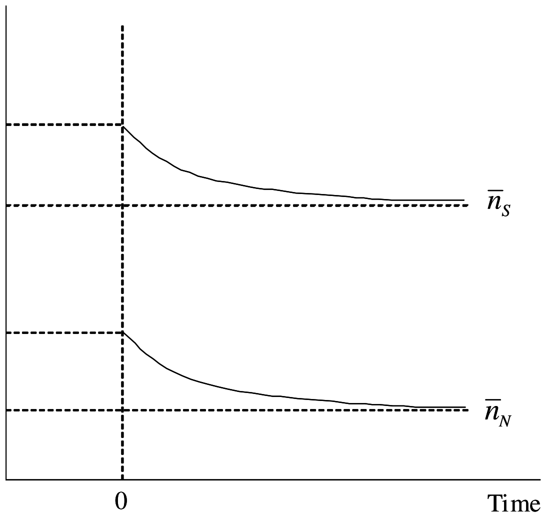

Figure 2: Threshold final goods

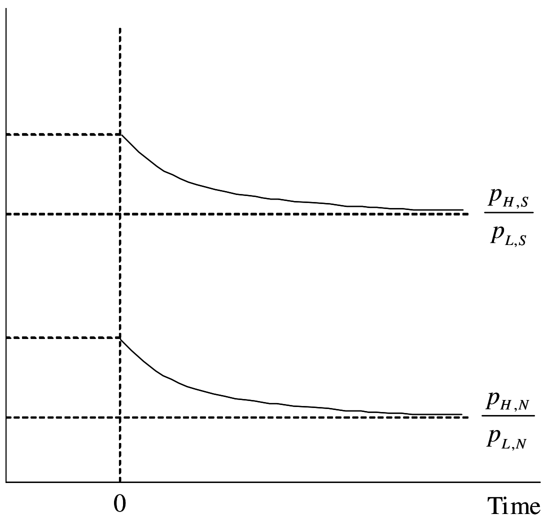

Figure 3: Relative price of High final goods

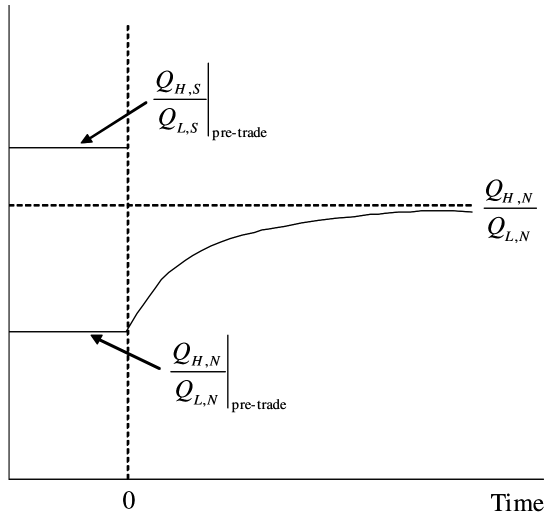

Figure 4: Relative productivity of High technological knowledge

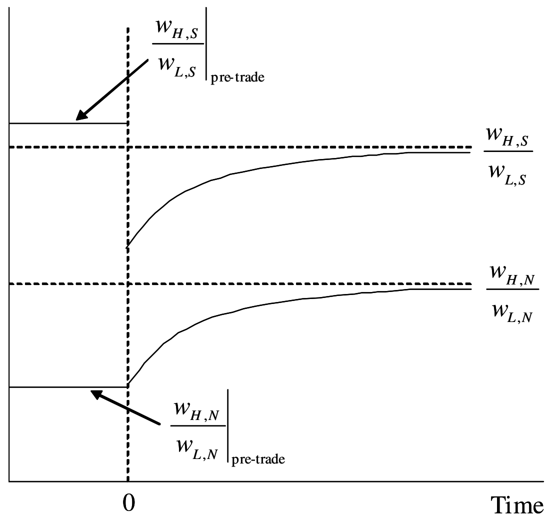

Figure 5: Intra-country wage inequality – high-skilled labor premium

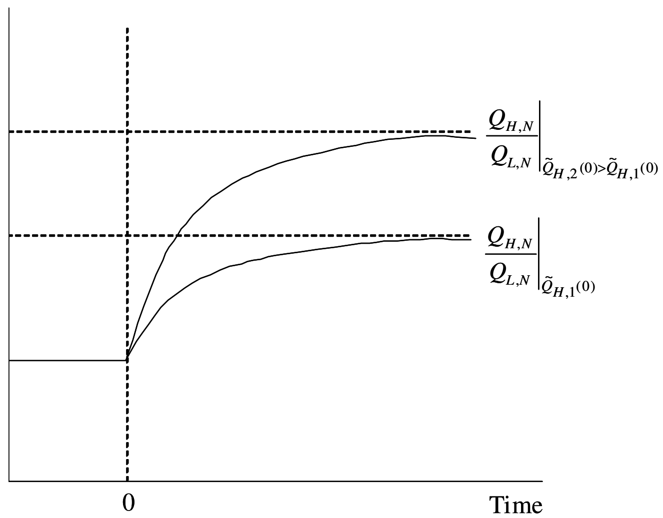

Figure 6: Changes in the path of technological knowledge bias