Human Capital Accumulation and Wage Inequality with Scale-Independent North-South Technological Diffusion

Oscar Afonso and Alvaro Aguiar

CEMPRE*, Faculdade de Economia, Universidade do Porto

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Please address correspondence to Alvaro Aguiar (alvaro@fep.up.pt), Faculdade de Economia, Universidade do Porto, Rua Roberto Frias 4200-464 Porto, PORTUGAL; +351226073595 (phone); +351226098736 (fax).

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Abstract

This paper analyzes the mechanisms, other than market size, through which international trade of intermediate goods incorporating state-of-the-art technological knowledge affects accumulation of human capital and wage inequality in the North and South.

Under North-South technological diffusion, endogenous economic growth depends on Schumpeterian R&D - innovation in the North and imitation in the South - and on accumulation of two types of human capital, wide and narrow. The former is school intensive while the latter is on-the-job-training intensive.

The effects of trade upon growth and wage inequality, through the price channel, are accessed in three analytical steps: (i) immediate level effects, (ii) steady-state effects, and (iii) transitional dynamics. Comparative steady-state statics and dynamics are used to uncover the mechanisms through which these effects are influenced by the technology of human capital accumulation.

The level effect brings about inter-country wage convergence. The comparative dynamics exercise with changes in the parameters of human capital accumulation shows that intra-country wage inequality is more likely to prevail under international trade, when such changes relatively enhance the world accumulation of the type of human capital that is relatively abundant in the South.

Keywords: North-South; International trade; Technological knowledge; Economic growth; Human capital; Wage inequality.

JEL classification: F16, F43, J24, J31, O31, O33.

1. Introduction

This paper analyses mechanisms through which endogenous accumulation of human capital influences the effects of North-South trade on economic growth and wage inequality inter and intra-country, in a dynamic setting, where:

- trade (in intermediate goods) is a vehicle for technological knowledge transfer;

- human capital accumulation interacts with the direction of technological knowledge arising from trade in intermediate goods.

Influential contributions to the literature about skill-biased technological change - Acemoglu and Zilibotti (2001) and Acemoglu (2002), for example - have considered this question in a framework where human capital endowments influence the direction of technological knowledge, which, in turn, drive the wage inequality dynamics. In these contributions, the market size channel - by which technologies that use the more abundant type of human capital are favoured - dominates this chain of effects.

Building on this literature, we consider, in this paper, the other direction of causality as well. That is, human capital accumulation, being endogenous, responds to incentives arising from technological knowledge change. In addition, we remove scale effects, in order to focus on the price channel, by which the type of human capital accumulation is influenced by the technologies used in the production of more expansive goods.

The technology of production of goods, human capital and R&D has been previously used and explained in Afonso and Aguiar (2003). The crucial feature of production of final goods is the concurrence of complementarity in the use of inputs and substitutability between types of technology. The inputs are human capital and quality-adjusted intermediate goods.

As for human capital, the time spent with its accumulation is split between school and on-the-job-training (OJT), following upon the ideas of Mincer (1993) and Lucas (1993). The relative intensity of the two modes of accumulation determines a specificity, which generates two types of human capital, wide and narrow. Relative to narrow human capital, wide human capital accumulation is school intensive, as well as more efficient in the production of final goods.

Contrary to human capital and final goods, intermediate goods are internationally tradable, and, as incorporators of the R&D output, are the vehicle for North-South technological knowledge transfer. The results of R&D improve the quality of intermediate goods, in line with the Schumpeterian setup, as formalized by, *eg*, Aghion and Howitt (1992). Such results are innovations in the North and imitations in the South.

Within this framework, the effects of trade upon growth and wage inequality are accessed in three analytical steps: (i) immediate level effects, (ii) steady-state effects, and (iii) transitional dynamics. By means of comparative statics and dynamics we are able to uncover the mechanisms through which these effects are influenced by the technology of human capital accumulation.

The paper now proceeds to characterise the domestic economy in the North and South. Then, in section 3, the dynamic equilibrium with trade in intermediate goods is derived, and the level, steady-state and transitional dynamics price channel effects of international trade extracted. Section 4 analyses comparative statics and dynamics resulting from alternative parameterizations of human capital accumulation. Some brief concluding remarks are presented in section 5.

2. Characterization of the domestic economy

In this section, drawing heavily on Afonso and Aguiar (2003), we define the productive setup, which is common to the North and South, except in what concerns the magnitude of some technology parameters, and some determinants of R&D activities.

Production of perfectly competitive final goods uses intermediate goods as inputs, together with human capital. Intermediate goods, in turn, use innovative or imitative designs as inputs, under monopolistic competition - as in Romer (1990).

Production technology

Final goods - Y - are continuously indexed by $n \in [0, 1]$. Following the contribution of Acemoglu and Zilibotti (2001), each final good is producible by two technologies, wide and narrow in our case. The wide technology uses wide human capital, WH, complemented with a continuum of wide-specific intermediate goods - x - indexed by $jW \in [0, JW]$. The narrow technology's inputs are narrow human capital, NH, complemented with a continuum of narrow-specific intermediate goods, indexed by $jN \in [0, JN]$. The quantity of each intermediate good is quality-adjusted - the constant quality upgrade is q, and k is the highest quality rung at time t. The production function of the n^{th} final good at time t is,

$$Y_n(t) = A\left\{\left[\int_0^{JW}\left(q^k\ x_n(k, jW, t)\right)^{1-\alpha}dj\right]\left(n\ h\ WH_n(t)\right)^{\alpha} + \right.$$
$$\left. + \left[\int_0^{JN}\left(q^k\ x_n(k, jN, t)\right)^{1-\alpha}dj\right]\left[(1-n)\ NH_n(t)\right]^{\alpha}\right\} \quad (1)$$

The integrals sum up the contributions of the two types of intermediate goods to production, and the expressions with exponent $\alpha \in]0, 1[$ represent the role of the specific human capital inputs. The production function is the same in both countries, except for a productivity level North-South gap: the term A - with $A_{Sth} < A_{Nth}$ - is a positive exogenous variable representing the level of productivity, dependent on the country's domestic institutions.

The human capital terms include two corrective factors for productivity differentials between the two types. An absolute productivity advantage of wide over narrow human capital is accounted for by $h \geq 1$, and a relative productivity advantage of either type of human capital is captured by the terms n and $(1-n)$. The final goods index n is arranged as a relative productivity ordering index: wide human capital is relatively more productive in producing final goods indexed by larger ns, and *vice-versa*. At each time t there is a competitive equilibrium threshold final good $\bar{n}$, where the switch from one technology to the other becomes advantageous, so that each final good is produced exclusively with one technology, either wide or narrow.

With perfect competition in final goods, economic viability of either type of technology depends on the relative productivity (h) and price of the specific type of human capital, as well as, because of complementarity in production, on the relative productivity and prices of the specific intermediate goods.

The prices of human capital depend on the quantities supplied to production, $WH_w(t)$ and $NH_w(t)$ - where the subscript w identifies the WH and NH actually at work in the production of final goods, as opposed to WH and NH in formation (at school or on-the-job-training). In relative terms, the productivity-adjusted quantity of wide human capital in production is $\frac{h\ WH_w(t)}{NH_w(t)}$.

As for the productivity and prices of intermediate goods, they depend on complementarity with either type of human capital, on the technological knowledge embodied, and on the mark-up - which, in turn, depends on the elasticity of demand by the producers of final goods. These determinants are summed up in

$$Q^{JW} = \int_0^{JW} q^{k(j W,t)\left[(1-\alpha)/\alpha\right]} dj \text{ and } Q^{JN} = \int_0^{JN} q^{k(j N,t)\left[(1-\alpha)/\alpha\right]} dj\,, \tag{2}$$

which are aggregate domestic quality indices, measuring domestic technological knowledge in each specific range of intermediate goods, adjusted by market power (which is the same for all monopolistic competitive producers). The ratio Q^{JW}/Q^{JN} is the relative productivity of the wide-specific intermediate goods, which is an appropriate measure of the wide-narrow technological knowledge bias.

The endogenous threshold final good $\bar{n}$ - determining the exclusive use of the wide technology in final goods $n > \bar{n}$ and of the narrow one for $n \leq \bar{n}$ - follows from equilibrium in the inputs markets. The resulting $\bar{n}$ at each time *t*, as a function of the determinants of economic viability of the two technologies, is

$$\bar{n}(t) = \left[1 + \left(\frac{Q^{JW}(t)}{Q^{JN}(t)} \frac{h\, WH_w(t)}{NH_w(t)}\right)^{\frac{1}{2}}\right]^{-1}, \tag{3}$$

The threshold final good $\bar{n}$ can be related to prices, by taking into account that in the threshold both a narrow technology firm and a wide technology firm should breakeven. This yields the ratio of index prices of final goods produced with wide and narrow technologies,

$$\frac{p^W}{p^N} = \left[\frac{\bar{n}}{1-\bar{n}}\right]^{\alpha}. \tag{4}$$

Equation (3) shows that either if the technology is highly wide-biased or if there is a large relative supply of *WH*, the fraction of industries using the wide technology is large and so $\bar{n}$ is small. By (4), small $\bar{n}$ implies a small relative price of wide final goods. In this situation, the demand for wide-specific intermediate goods is low, discouraging R&D activities aimed at improving their quality. Therefore, human capital structure influences the direction of R&D through the price channel - incentives to develop specific technologies are weaker when the prices of final goods produced with these technologies are lower due to their use of the relatively abundant type of human capital. This price channel shows up in various papers by Acemoglu (*eg* 2002), although always dominated by the market size effect, which, in our case, is negligible.

Aggregate production of final goods in equilibrium - *Y*(*t*), which serves as numeraire - is obtained by integration, and, being dependent on the threshold $\bar{n}$, can be expressed in terms of its determinants,

$$Y(t) = exp\,(-1)\,A^{1/\alpha}(1-\alpha)^{2\frac{1-\alpha}{\alpha}}\left[\left(Q^{JN}(t)\;NH_w(t)\right)^{\frac{1}{2}} + \left(Q^{JW}(t)\;h\,WH_w(t)\right)^{\frac{1}{2}}\right]^2, \tag{5}$$

clearly showing that growth is driven by progress in technological knowledge and by human capital accumulation.

Individuals and human capital accumulation

We turn now to individual behavior, in order to define human capital accumulation and its employment. A time-invariant number of heterogeneous individuals decide the allocation of time and income. Time is divided between education to accumulate human capital, and working to earn a share of the composite final output, proportional to the individual's human capital. Income is partly spent directly on the consumption of the composite final good, and partly lent in return for future interest.

Heterogeneity is present in two related individuals' characteristics. One is the ability level – a – uniformly distributed over a range $[0, 1]$, and the other is the type of human capital – WH and NH. For simplicity, we consider an exogenous threshold ability $\bar{a}$, such that individuals with high ability – $a > \bar{a}$ – accumulate the wide type, while low ability individuals – $a \leq \bar{a}$ – are only able to accumulate the narrow type.

Assuming a CIES instantaneous utility function and a homogeneous discount rate ρ, the infinite horizon lifetime utility of an individual is

$$U(t) = \int_0^{\infty}\left[\frac{c(t)^{1-\theta}-1}{1-\theta}\right]exp(-\rho t)\,dt\,. \tag{6}$$

where $c(t)$ is individual consumption at time t.

Savings consists of accumulation of financial assets - K, with return r - in the form of ownership of the firms that produce intermediate goods. The value of these firms, in turn, corresponds to the value of patents in use. The budget constraint equalizes savings to income earned minus consumption,

$$\dot{K}(t) = r\,(t)\,K(t) + \left(1 - u_S(t) - u_T(t)\right)\,w^m(t)\,m(t) - c\,(t)\,. \tag{7}$$

where:

- m indexes the type of human capital;
- $w^m(t)$ is the wage per unit of m-type human capital, at time t;

- $u_S(t)$ and $u_T(t)$ are the fractions of time t that are spent accumulating human capital at school and on-the-job-training, respectively.[1]

Turning now to the production of human capital, individuals accumulate either type *WH* or *NH* (constrained by the ability level), using school and OJT as inputs. Productivity of the time spent in School and OJT increases with the amount of the individual's human capital - as in Lucas (1988). We consider the following CES accumulation function:

$$\begin{cases} \dot{WH}(t) = \left\{ \left[\varphi^{WH} \left(\chi_S u_S(t) \right)^{\phi} + \left(1 - \varphi^{WH} \right) \left(\chi_T u_T(t) \right)^{\phi} \right]^{1/\phi} - \delta^{WH} \right\} WH(t), \text{ for } a > \bar{a} \\ \dot{NH}(t) = \left\{ \left[\varphi^{NH} \left(\chi_S u_S(t) \right)^{\phi} + \left(1 - \varphi^{NH} \right) \left(\chi_T u_T(t) \right)^{\phi} \right]^{1/\phi} - \delta^{NH} \right\} NH(t), \text{ for } a \leq \bar{a} \end{cases}, \quad (8)$$

where δ^m is the depreciation rate of *m*-type human capital; χ_S and χ_T are efficiency parameters of schooling and OJT, respectively; and $\varphi^m \in [0,1]$ is the intensity parameter, which determines the relative contribution of the two modes to human capital accumulation.[2] We assume $\varphi^{WH} > \varphi^{NH}$ and $\chi_S \geq \chi_T$, so that *WH* is relatively school intensive and school is relatively more productive in the production of *WH*, considering Grossman and Shapiro's (1982) and Mincer's (1993) suggestion that school provides general human capital, more versatile or adaptable to changing environments, while OJT is more specific.

The CES formulation allows schooling and OJT to be either complements or substitutes, depending on the value of the substitution parameter - complements if $\phi < 0$ and substitutes if $0 < \phi \leq 1$. According to Mincer (1993), both cases are possible. A high degree of substitutability, coupled with the assumed higher efficiency of schooling, means that most of the human capital skills necessary to the production of final goods are better obtained at school. Whereas strong complementarity indicates that school, in spite of higher efficiency, is far from providing all such necessary skills, requiring additional on-the-job-training in significant amounts. In a scenario of strong substitutability, constraining the measurement of human capital to formal schooling tends to be sufficient, especially for wide human capital, which uses school more intensively. On the contrary, the case of complementarity supports the claims in the growth-human capital literature that the lack of an empirically robust relationship is

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[1] Following Mincer (1993), we consider that OJT is costly, in the sense that it requires time away from work.

[2] In order to simplify the computations of the dynamics - sections 3 and 4, below - we assume $\delta^{WH} = \delta^{NH} = \delta$ and $\varphi^{WH} = 1\text{-}\varphi^{NH}$.

partially attributable to the exclusion of OJT from the measures of human capital - *eg* Lucas (1993).

In section 4, below, we explore the dynamic implications of substitutability *versus* complementarity, as well as changes in the other parameters of the accumulation function (8), on growth and wage inequality under international trade.

Each individual maximizes lifetime utility (6), subject to the budget constraint (7) and to the human capital accumulation (8). The solution for the consumption path, which is independent of the individual's human capital, is the standard Euler equation

$$\frac{\dot{c}(t)}{c(t)} = \frac{1}{\theta}\left(r(t) - \rho\right). \tag{9}$$

Regarding time-allocation to school relative to OJT, the optimal ratio depends on the type of human capital,

$$\left.\frac{u_S(t)}{u_T(t)}\right|_m = \left[\frac{\varphi^m \chi_S^\phi}{\left(1-\varphi^m\right)\chi_T^\phi}\right]^{\frac{1}{1-\phi}}. \tag{10}$$

If schooling and OJT are substitutes (but not perfect), the optimal time-allocation ratio is positively related to the efficiency ratio χ_S / χ_T, and *vice-versa* in the case of complements. For example, in the case of complements, an increase in the time allocated to the input with the higher efficiency parameter requires a greater increase in the time allocated to the input with the lower efficiency parameter.

An important arbitrage condition inter-relates the returns from the different types of assets. An interior solution to the individual maximization problem requires positive amounts of both assets, *K* and *WH* (or *NH*), which is not sustainable unless their returns are equalized at all times. The following condition ensures this:

$$\frac{\dot{w}^m(t)}{w^m(t)} = r(t) + \delta^m - \left\{\left(\varphi^m \chi_S{}^\phi\right)^{(1-\phi)^{-1}} + \left[\left(1-\varphi^m\right)\chi_T{}^\phi\right]^{(1-\phi)^{-1}}\right\}^{\frac{1-\phi}{\phi}} \tag{11}$$

R&D technology

Together with human capital, R&D drives North and South economic growth. A brief description of the technology of R&D follows.

R&D activities in the North, when successful, result in innovative designs for the manufacture of intermediate goods, which increase their quality. In the South, R&D success means imitation of a state-of-the-art design. The determinants of the probability of success are at the heart of the Schumpeterian R&D models - *eg* Aghion and Howitt (1992).

Let $pb_{Nth}(k, jm, t)$ denote the instantaneous probability, in the North, of successful innovation in the next higher quality $(k(jm,t)+1)$ of intermediate good jm, which complements human capital type m in the production of final goods.

$$pb_{Nth}(k, jm) = rs_{Nth}(k, jm)\, lr_{Nth}(k, jm)\, lm_{Nth}\, cp_{Nth}(k, jm), \qquad (12)$$

where:

(i) rs_{Nth} is the flow of domestic final good resources devoted to R&D.

(ii) $lr_{Nth}(k, jm) = \beta_{Nth} q^{k(jm)}$ represents learning by R&D, which is the positive effect of accumulated public knowledge from past successful research – *eg* Grossman and Helpman (1991, chap. 12).

(iii) $lm_{Nth} = m_w^{-1}$, is the adverse effect of market size, such that the difficulty of replacing old intermediate goods for new ones is proportional to the size of the market, which is measured by the respective human capital in production. That is, we include in R&D the costs of scale increasing, due to coordination, processing of ideas, informational, organisational, marketing and transportation costs, as reported by authors like Becker and Murphy (1992), Alesina and Spolaore (1997), and Dinopoulos and Thompson (1999).[3]

(iv) $cp_{Nth}(k, jm) = \zeta_{Nth}^{-1} q^{-\alpha^{-1} k(jm)}, \zeta_{Nth} > 0,$ is the adverse effect caused by the increasing complexity of quality improvements (*eg* Kortum, 1997).

The South mimics the R&D process of the North, aiming at imitation of the current best qualities. The probability of success - $pb_{Sth}(k, jm, t)$ - in imitating the current higher quality $(k(jm,t))$ in intermediate good jm, is similar to $pb_{Nth}(k, jm, t)$, multiplied by a catching-up factor.

$$pb_{Sth}(k, jm) = rs_{Sth}(k, jm)\, lr_{Sth}(k, jm)\, lm_{Sth}\, cp_{Sth}(k, jm)\, bp_{Sth}(k, jm), \qquad (13)$$

The relevant differences are:

(ii') $lr_{Sth}(k, jm) = \beta_{Sth}\, q^{k_{Sth}(jm)}, 0 < \beta_{Sth} < \beta_{Nth}, k_{Sth} \leq k$.

(iv') $cp_{Sth}(k, jm) = \zeta_{Sth}^{-1} q^{-\alpha^{-1} k(jm)}, \zeta_{Nth} > \zeta_{Sth} > 0,$ *ie*, the complexity cost of imitation is lower than the innovation's - as argued by Mansfield *et al.* (1981) and Teece (1977).

[3] Dinopoulos and Thompson (1999), in particular, provide micro foundations for this effect.

The catching-up term sums up positive effects of imitation capacity and backwardness, in the following form:

$$bp_{Sth}(k, jm) = \left[1 + \frac{exp(\tilde{m}_w)}{1 + exp(\tilde{m}_w)} \right]^{\sigma_1} \left[-\left(\tilde{Q}^{Jm}\right)^2 + \tilde{Q}^{Jm} \right]^{-\sigma_2 + \tilde{Q}^{Jm}} \ , \ \sigma_1, \sigma_2 > 0 \ , \qquad (14)$$

where

$\tilde{m}_w = m_{Sth,w}/m_{Nth,w} < 1$ is the South relative level of m human capital in production;

$\tilde{Q}^{Jm} = \dfrac{Q_{Sth}^{Jm}}{Q_{Nth}^{Jm}} < 1$ is the South relative technological knowledge in m-specific intermediate goods.

The first term within square brackets captures the idea - put forward by Nelson and Phelps (1966) and, more recently, by Benhabib and Spiegel (1994), among others - that human capital enhances imitation capacity, thereby speeding up convergence with the innovator. Parameter σ_1 affects how fast the probability of successful imitation rises as the human capital gap falls.

The benefits of relative backwardness are captured by the second term in square brackets - similar to Papageorgiou (2002). The function is quadratic and, once affected by the exponent, yields an increasing (in the technological knowledge gap) advantage of backwardness - where the size of σ_2 affects the speed at which the probability of successful imitation falls as the technological knowledge gap falls.

3. North-South trade in intermediate goods

Once engaged in international competition, the successful monopolist producers of intermediate goods have access to the entire world market. At each point in time, the successful producer of intermediate good j uses the latest technology, q^k. Whether it is an innovative (Northern producer) or imitated (Southern producer) technological design, it depends on price competition in the world market.

International limit pricing

Competitiveness of the imitators rests on the assumption that the South has a marginal cost advantage in the production of final goods, which carries out to intermediate goods - $MC_{Sth} < MC_{Nth} = 1$. This advantage confines worldwide optimising limit pricing by the relevant competitive monopolists - *eg* Grossman and Helpman (1991, chap. 12).

The international price index of the *m*-specific intermediate goods - p_{Jm} - is a weighted average of the mark-ups resulting from the three possible successful R&D outcomes, which are the following (for further details, see Afonso and Aguiar, 2003):
(i) a Northern entrant competes with a Northern incumbent, at the same marginal cost, but better quality, extracting the highest mark-up, equal to the one that would prevail in autarky;
(ii) a Southern entrant, with lower marginal cost, competes in the same quality rung with a Northern incumbent;
(iii) a Northern entrant competes with a Southern incumbent, such that the improvement in quality overcomes the marginal cost disadvantage.

Level effects in the South

In this international trade context - perfectly mobile intermediate goods and immobile human capital -, the South has access to the technological knowledge embodied in the state-of-the-art intermediate goods, either by imitation of the latest innovations, or by importing state-of-the-art intermediate goods.[4]

The immediate improvement in the level of technological knowledge available to the South is a static benefit of international trade, which affects the levels of productivity and prices of goods and factors, yielding convergence towards the North. The relevant technological knowledge ratio for the South is the Northern one, as is apparent in the expression for the South's threshold final good, which, as derived above, summarizes the technology of production and determines prices of final goods in the South.

$$\bar{n}_{Sth}(t) = \left[1 + \left(\frac{Q_{Nth}^{JW}(t)}{Q_{Nth}^{JN}(t)} \frac{h\, WH_{Sth,w}(t)}{NH_{Sth,w}(t)} \right)^{\frac{1}{2}} \right]^{-1}, \tag{15}$$

Since the technological gap is always favourable to the North in either specific knowledge – *ie*, $Q_{Nth}^{Jm} > Q_{Sth}^{Jm}$ –, the access to Northern technological knowledge through

[4] However, Southern technological knowledge - Q_{Sth}^{Jm} - is not equalized with the North, because, in 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_{Nth}^{Jm}.

trade increases immediately marginal productivities of *WH* and *NH*, and thus wages of both types, in the South - w_{Sth}^{WH} and w_{Sth}^{NH} .

Increases in Southern wages, though, are not balanced, in general. For instance, if the wide-specific technological gap is relatively larger, and the North is relatively *WH* abundant in terms of initial endowments, *ie*,

$$\frac{Q_{Nth}^{JW}(0)}{Q_{Sth}^{JW}(0)} > \frac{Q_{Nth}^{JN}(0)}{Q_{Sth}^{JN}(0)} \quad \text{and} \quad \frac{WH_{Nth}(0)}{NH_{Nth}(0)} > \frac{WH_{Sth}(0)}{NH_{Sth}(0)}, \tag{16}$$

then the level effect increases wages inequality - *ie*, the wide human capital premium, $w_{Sth}^{WH} / w_{Sth}^{NH}$. This is caused by the increase in wide-specific bias in available technological knowledge, which, due to complementarity in the production of final goods, increases the demand for *WH* more than for *NH*.

Dynamic equilibrium

In contrast with the level effect, growth effects of trade in intermediate goods bear upon the South as well as the North, due to international interdependence.

North-South interaction is show up clearly in dynamic equilibrium. The growth of available technological knowledge depends on the returns to innovation, which, in turn, depend on the probability of successful imitation, through international competition in intermediate goods. 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 available technological knowledge through creative destruction. The expression for the equilibrium growth of available wide-specific (for example) technological knowledge - detailed derivation in Afonso and Aguiar (2003) - reflects this dynamic feedback,

$$\frac{\dot{Q}_{Nth}^{JW}(t)}{Q_{Nth}^{JW}(t)} = \left[\beta_{Sth}\, \zeta_{Sth}^{-1}\, bp_{Sth}^{WH}(t)\, \tilde{Q}^{JW}(t)\, h\, (1-\alpha)^{\alpha^{-1}}\, D^{WH}(t) - r_{Sth}(t)\right]\left[q^{(1-\alpha)\alpha^{-1}} - 1\right], \tag{17}$$

where

$$D^{WH}(t) \equiv \frac{WH_{Sth,w}(t)}{WH_{Sth,w}(t) + WH_{Nth,w}(t)} \left(A_{Sth} p_{Sth}^{WH}(t)\right)^{\alpha^{-1}} + \frac{WH_{Nth,w}(t)}{WH_{Sth,w}(t) + WH_{Nth,w}(t)} \left(A_{Nth} p_{Nth}^{WH}(t)\right)^{\alpha^{-1}}.$$

Two points related to the deliberate removal of scale effects are worth remarking in equation (17). First, the equilibrium growth rate of technological knowledge is independent of its scale, since it is not affected by the rung of quality *k* - as in Barro and Sala-i-Martin (2004, chap. 7), the positive influence of the quality rung on profits and on the learning effect is exactly offset by the negative one on the complexity cost. Second, the market scale effects are isolated in term D^{WH}, where they appear negligibly. This almost complete removal is attained by offsetting the positive effect of market scale on the size of profits with the adverse effect on its duration.[5]

By complementarity in the production of final goods, the equilibrium rate of growth of internationally available *m*-specific technological knowledge translates into the growth of demand for *m*-type human capital. Interrelated with the dynamics of international prices of intermediate goods and domestic prices of final goods (p_{Jm}, p^m_{Nth} and p^m_{Sth}), it yields the following equilibrium wage dynamics:

$$\begin{aligned}\frac{\dot{w}^m_{Nth}(t)}{w^m_{Nth}(t)} &= \frac{1}{\alpha}\frac{\dot{p}^m_{Nth}(t)}{p^m_{Nth}(t)} + \frac{1-\alpha}{\alpha}\frac{\dot{p}_{Jm}(t)}{p_{Jm}(t)} + \frac{\dot{Q}^{Jm}_{Nth}(t)}{Q^{Jm}_{Nth}(t)} \\ \frac{\dot{w}^m_{Sth}(t)}{w^m_{Sth}(t)} &= \frac{1}{\alpha}\frac{\dot{p}^m_{Sth}(t)}{p^m_{Sth}(t)} + \frac{1-\alpha}{\alpha}\frac{\dot{p}_{Jm}(t)}{p_{Jm}(t)} + \frac{\dot{Q}^{Jm}_{Nth}(t)}{Q^{Jm}_{Nth}(t)}\end{aligned} . \tag{18}$$

The path of *m*-wages in each country depends on the path of domestic demand for *m*-type human capital, which, in turn, depends on the evolution of,

(i) the domestic range of the *m*-specific 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.

The domestic equilibrium interest rate, at each point in time, is derived, as a function of wage dynamics, from the necessary condition for optimization by individuals (11). Then, equilibrium growth in consumption, in turn, results from the first necessary condition - the Euler equation (9).

Steady-state effects

In particular, the steady-state equilibrium is characterized by constant growth, common to both countries, clearly driven by R&D in the North and human capital accumulation,

[5] The positive effect on the size of monopolist's profits comes from complementarity in production - the larger is the market for *m*-specific intermediate goods, the greater are profits at each time *t*; while the offsetting negative effect on duration of profits is the scale-proportional difficulty in introducing new quality intermediate goods - term (iii) in the probability of successful R&D, equation (12).

$$\frac{\dot{Q}_{Nth}^{JW}}{Q_{Nth}^{JW}}+\frac{\dot{WH}_{w}}{WH_{w}}=\frac{\dot{Q}_{Nth}^{JN}}{Q_{Nth}^{JN}}+\frac{\dot{NH}_{w}}{NH_{w}}=\frac{\dot{Y}}{Y}=\frac{\dot{c}}{c}=\theta^{-1}\left(r^{ss}-\rho\right)=g\,, \tag{19}$$

where

(i) $\frac{\dot{WH}_{w}}{WH_{w}}=\frac{\dot{WH}_{Nth,w}}{WH_{Nth,w}}=\frac{\dot{WH}_{Sth,w}}{WH_{Sth,w}}$ and $\frac{\dot{NH}_{w}}{NH_{w}}=\frac{\dot{NH}_{Nth,w}}{NH_{Nth,w}}=\frac{\dot{NH}_{Sth,w}}{NH_{Sth,w}}$;

(ii) r^{ss} is the steady-state interest rate, common to both countries, resulting from constant growth of wages (equation 11), which, in turn result (equation 18) from constant prices of non-tradable and tradable goods and from constant growth of available technological knowledge.

The common steady-state growth rates of human capital imply the maintenance of steady-state North-South gaps in human capital and technological knowledge. While complete convergence in available technological knowledge is instantaneous with international trade (level effect), domestic levels may not converge completely, that is $\tilde{Q}^{JW}$, $\tilde{Q}^{JN}$, $\tilde{WH}$ and $\tilde{NH}$ may remain below one.

In what regards wage inter and intra-country inequality in steady-state, the common growth rates

$$\text{(i)}\quad \left.\frac{\dot{w}_{Nth}^{m}}{w_{Nth}^{m}}\right|^{ss}=\left.\frac{\dot{Q}_{Nth}^{Jm}}{Q_{Nth}^{Jm}}\right|^{ss}=\left.\frac{\dot{w}_{Sth}^{m}}{w_{Sth}^{m}}\right|^{ss}$$

$$\Downarrow \tag{20}$$

$$\text{(ii)}\quad \left.\left(\frac{\dot{w}_{Sth}^{WH}}{w_{Sth}^{WH}}-\frac{\dot{w}_{Sth}^{NH}}{w_{Sth}^{NH}}\right)\right|^{ss}=\left.\left(\frac{\dot{w}_{Nth}^{WH}}{w_{Nth}^{WH}}-\frac{\dot{w}_{Nth}^{NH}}{w_{Nth}^{NH}}\right)\right|^{ss}=\left.\left(\frac{\dot{Q}_{Nth}^{JW}}{Q_{Nth}^{JW}}-\frac{\dot{Q}_{Nth}^{JN}}{Q_{Nth}^{JN}}\right)\right|^{ss},$$

imply

(i) maintenance of inter-country inequality, in spite of partial immediate convergence (level effect in the South);

(ii) possibly decreasing intra-country wage premia, at a constant rate, in spite of the immediate increase in the South (level effect in the case of conditions 16, above).

In order to examine the evolution of gaps and inequality - after the immediate level effects - towards steady-state, we proceed now with transitional dynamics analysis.

Transitional dynamics

Numerical calculation of the system of five differential equations describing dynamic equilibrium - which has involved parameter calibration and sensitivity analysis based on empirical literature and theoretical conditions, as exposed 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 wage inequality and human capital gaps. Figures 1-5 compare the autarkic steady-state paths with the ones caused by openness - a shift, at time zero, to free trade of intermediate goods -, assuming, without loss of generality, the starting conditions stated in (16).

In order to relate the effects to the price channel, figure 1 depicts the paths of relative prices of final goods. The relative price of Southern *WH* final goods drops at t_0, due to the level effect - *ie*, the access to the Northern technological knowledge induces immediate partial convergence in prices of non-tradables. From then on, relative prices of *WH* goods drop continuously in both countries towards the constant steady-state levels - this is because Northern *WH* technological knowledge bias spreads internationally, directing R&D towards *WH*-specific intermediate goods and, thus, increasing their productivity, which, in turn, diminishes the perfectly competitive domestic relative prices of *WH* final goods.

Because of technological leadership, the relative price that operates the price channel is always the one commanding the direction of technological knowledge in the North. In pre-trade, this relative price is $p_{Nth}^{WH} / p_{Nth}^{NH}$, *ie* the relative price of *WH* final goods, which are feeding the demand for *WH*-specific intermediate goods. With trade, even though final goods are non-tradable, their prices in both the North and South are commanding the direction of Northern technological knowledge, because of tradability of the intermediate goods necessary to produce final goods in both countries. Due to differences in endowments (conditions in equation 16), the North-South average relative price of *WH* goods is always higher than the one prevailing in the pre-trade North. Therefore, through the price channel, international trade bias available technological knowledge in favour of *WH*-specific intermediate goods, as figure 2 shows - comparing the pre-trade bias in the North with the bias in world available technological knowledge. This, in turn, stimulates Northern relative demand for the complementary input, *WH*.

Figure 3 shows the dynamics of intra-country wage inequality. In the North, the stimulus to the demand for *WH* attenuates the path of declining inequality, relative to what would have prevailed under pre-trade. In pre-trade, the price channel in the North operated strongly in favour of the relatively scarce human capital, *NH*.

In pre-trade South, relative scarcity causes increasing inequality, which is reinforced by the level effect - immediately increasing availability of state-of-the-art, *WH*-biased, intermediate goods. However, the strong reversal of the price channel effect - apparent in figure 2, comparing the pre-trade bias in the South with the bias in world available technological knowledge - redirects the path of the relative wage premium in favour of declining inequality, following the same slope as the North.[6]

As for inter-country inequality, the relative level of wages jumps at t_0 in favour of the South, due to the rise in productivity brought about by newly available state-of-the-art intermediate goods. However, from then on, inequality remains constant, because the path of productivity becomes common to both countries. This is shown in figure 4, where, in addition, the jump is more accentuated for $w_{Sth}^{WH} / w_{Nth}^{WH}$, in coherence with the intra-South unbalanced gains from the level effect. In spite of Southern gains, though, human capital international immobility and differences in domestic institutions (more productive in the North, recall the description of technology in section 2, above) sustain wage inequality in favour of the North.

In figure 5, international trade affects human capital accumulation, of both types, thereby changing inter-country gaps in favour of the South. Accumulation in the South is immediately stimulated by higher wages, due to the level effect, and from then on continuously adjusts the levels to their higher steady-states. The right hand side of figure 5 illustrates the intertemporal trade-off between work and accumulation of human capital. Facing the permanent increase in wages brought about by trade in intermediate goods at t_0, Southern individuals adjust the trajectory of time allocation, devoting more time to school and on-the-job-training, and less time to work. In other words, the ratio

$$\frac{[1-(u_S+u_T)]_{Sth}}{[1-(u_S+u_T)]_{Nth}}$$

[6] As equation (20) shows, the common slope of the inequality path is determined, in steady-state, by the negative growth of the wide-narrow technological bias, which is depicted in figure 2.

falls at t_0, for both types of individuals. Then it adjusts smoothly back to its steady-state level, around 1. The path of the ratios of human capital at work reflects this dynamic adjustment.

4. Comparative statics and dynamics related to human capital accumulation

The previous section explored the price channel effects of international trade on wage inequality and human capital accumulation. Now, through comparative statics and dynamics - obtained through numerical simulation -, we are able to assess to what extent the technology of human capital accumulation, in turn, influences the dynamic - steady-state and transitional - effects of trade.

Comparative steady-state statics

Table 1 summarizes the direction of change in steady-state growth and some relative levels of human capital and prices, due to changes in human capital-related parameters.

Table 1. Comparative steady-state statics - growth and relative levels

	∂g	$\partial\left(\frac{p_{Nth}^{WH}}{p_{Nth}^{NH}}\right), \partial\left(\frac{p_{Sth}^{WH}}{p_{Sth}^{NH}}\right)$	$\partial\left(\frac{m_{Sth}}{m_{Nth}}\right)$
$\partial\varphi^{WH}$	+	–	+
$\partial\chi_S$	+	–	+
$\partial\chi_T$	+	+	–
$\partial\delta$	–	+	+
$\partial\phi$	+	–	+

Recalling the technology of production of human capital (8), the steady-state growth rate, common to the North and South, increases with

(i) more intensive use of the more productive mode of human capital production - schooling;

(ii) higher efficiency of either input to the production of *WH* and *NH*;

(iii) lower depreciation of human capital;

(iv) higher substitutability between the two modes of human capital production, which allows more extensive use of the more productive one.

The third column in table 1 accounts for the changes in relative prices of final goods, through which the price channel operates. More intensive use of the more productive mode - either from increases in intensity φ^{WH}, or enhanced efficiency χ_S, or through higher substitutability ϕ - increases the relative advantage in accumulating *WH*, which is the type of human capital that uses more intensively the more productive mode. The rise in the relative supply of *WH* lowers its relative wage, thereby increasing its use in final production and lowering the relative price of *WH* final goods.

Price channel effects explain the changes in inter-country gaps in the accumulation of human capital. As the relative price of *NH* final goods rises with the more intensive use of schooling, technological knowledge is directed towards *NH*-specific intermediate goods. Since the South is relatively abundant in *NH*, it benefits relatively more in terms of productivity, and thus wages, which induces the reduction in human capital gaps - first, second and fourth effects in the fourth column of table 1.

Comparative dynamics of intra-country inequality

Figures 6-8 illustrate the mechanisms behind the changes in the path of intra-country wage inequality, resulting from contrasting scenarios. The baseline scenario is the one behind figures 1-5, above. Scenario A, which exemplifies a continuum of departures from the baseline human capital production parameters - in the direction of relative improvements in the accumulation of narrow human capital - has been obtained by alternatively

(i) decreasing φ^{WH}, the intensity of schooling;

(ii) decreasing χ_S, the efficiency of schooling;

(iii) increasing χ_T, the efficiency of OJT;

(iv) decreasing ϕ, the degree of substitutability.

Figure 8 shows that, in contrast with the baseline case, trade causes wages in scenario A to follow a path of increasing inequality in both countries. International trade reverts pre-trade decreasing inequality in the North. In the South, however, trade attenuates pre-trade increasing inequality, which resulted from the Southern relative abundance of narrow human capital - condition (16).[7]

The mechanism is, once again, the price channel effect. Improvements in the production of *NH* enhance its accumulation, thereby increasing its relative supply and lowering its relative wage, which, in turn, incentives its use in final production and lowers the relative price of *NH* final goods. Accordingly, figure 6 shows that the level effect drop in the relative price of *WH* goods is less pronounced than in the baseline. Therefore, compared with the one prevailing in the pre-trade North, the North-South average relative price of *WH* goods is even greater than in the baseline scenario. This accentuates the technological knowledge bias in favor of wide-specific intermediate goods. With sufficiently contrasting parameter values - as in figure 7 - scenario A reverts both the pre-trade and baseline paths of available technological knowledge bias. In summary, in scenario A, enhanced accumulation of *NH* decreases the relative price of *NH* final goods, which, in turn, strongly re-directs R&D towards designs for wide-specific intermediate goods.

Once relative prices of goods attain their constant steady-state levels, the only source of intra-country wage inequality is the direction of technological knowledge (recall expression 20). Due to complementarity in the production of final goods, the steady-state increasing bias in favor of wide-specific intermediate goods determines the steady-state path of increasing *WH* premia, as in scenario A depicted in figure 8.

5. Concluding remarks

This paper emphasizes the mechanisms, other than market size, through which international trade of intermediate goods incorporating state-of-the-art technological knowledge affects accumulation of human capital and wage inequality in the North and South. We have learned that such mechanisms, working through the price (of final goods) channel, are better understood if transitional dynamics, as well as comparative steady-state statics and dynamics related to human capital parameters, are worked out.

Our results can be interpreted at the light of the 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

[7] We remark that improvements in the efficiency of on-the-job-training, in particular, increase the North and South steady-state growth rate - see table 1, above - while favoring intra-country wage inequality.

inter and intra-country wage inequality result similarly from technological bias, but are however induced through the price channel under international trade, conveniently insulated from market size effects.

In particular, the comparative dynamics exercise with changes in the parameters of the production functions of human capital shows that intra-country wage inequality is more likely to prevail under international trade, when such changes relatively enhance the world accumulation of the type of human capital that is relatively abundant in the South.

Appendix. Baseline parameter values

Parameter calibration is based on empirical literature and theoretical conditions.

Baseline parameter values

Parameter	Value	Parameter	Value	Parameter	Value
A_{Nth}	1.56	β_{Sth}	1.00	ρ	0.03
A_{Sth}	1.00	ζ_{Nth}	4.00	δ^{m}	0.02
α	0.60	ζ_{Sth}	2.00	φ^{VH}	0.60
h	1.20	σ_1	0.25	χ_S	0.09
MC_{Sth}	0.50	σ_2	0.60	χ_T	0.07
β_{Nth}	1.60	θ	1.05	ϕ	0.05

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

There are no empirical estimates for the value of σ_1 and σ_2. The former must be greater, but not much greater, than zero, in order to guarantee a moderate but important impact of human capital on the probability of imitation. The value for σ_2 is set in order to guarantee that the technological knowledge progress in the South benefits from the relative backwardness of the country.

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

The human capital depreciation rate, δ, is in line with estimates by Mincer and Ofek (1982).

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Figure 1. Relative price of *WH* final goods

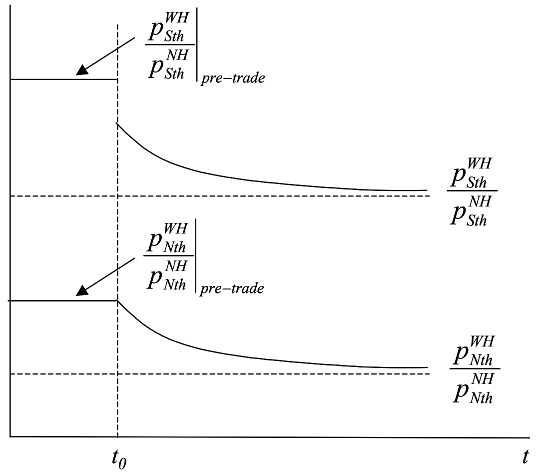


Figure 2. Relative productivity of wide technological knowledge

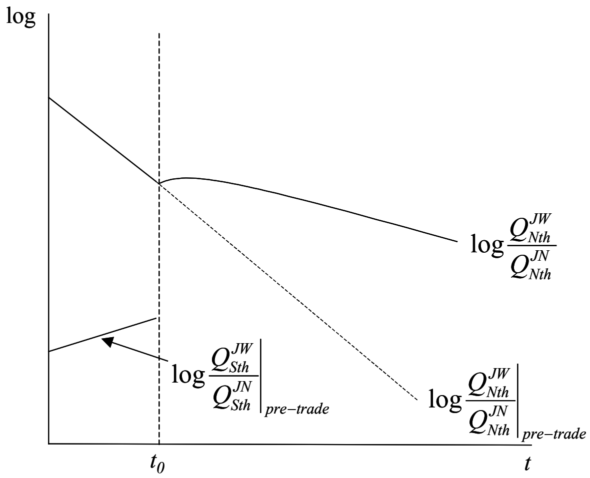


Figure 3. Intra-country inequality - relative wage of wide human capital

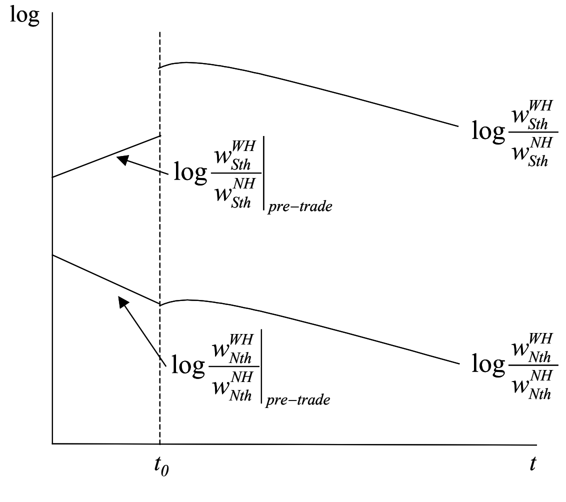


Figure 4. Inter-country inequality –
Southern relative wages

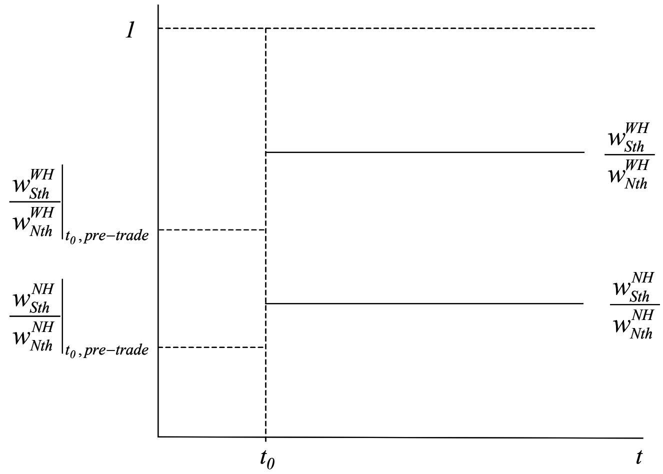
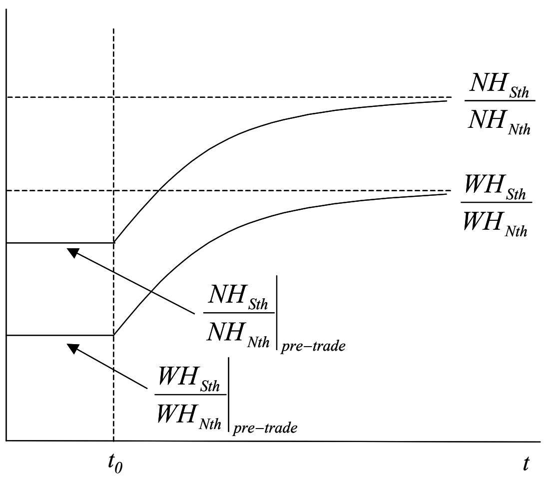


Figure 5. Relative levels of human capitals

Relative levels of Southern human capitals



Relative levels of Southern human capitals at work

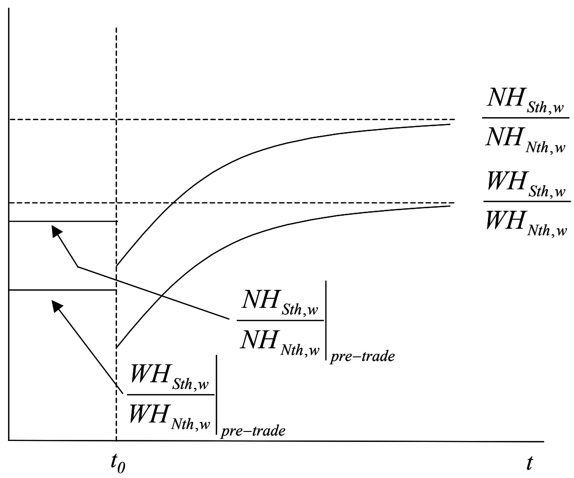


Figure 6. Comparative dynamics -
relative price of *WH* final goods

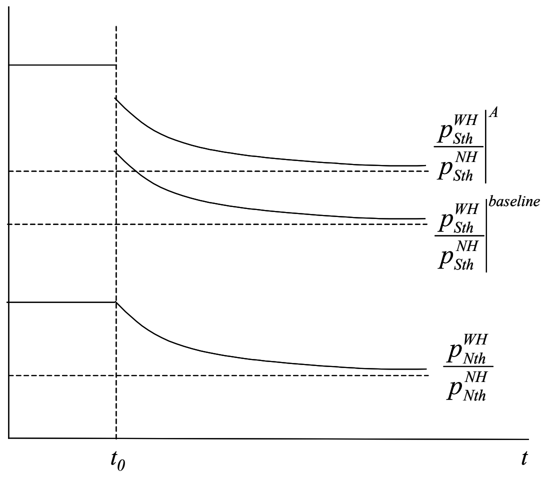


Figure 7. Comparative dynamics -
relative productivity of wide technological knowledge

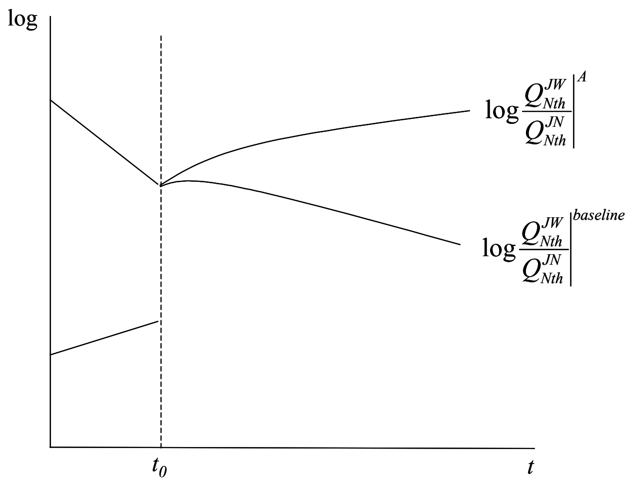


Figure 8. Comparative dynamics -
Intra-country inequality