Hitotsubashi Journal of Economics 54 (2013), pp.203-220. © Hitotsubashi University

EFFECTS OF INTERNATIONAL DIFFUSION OF A GENERAL PURPOSE TECHNOLOGY ON WAGE INEQUALITY

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Received September 2012; Accepted April 2013

Abstract

This paper studies the effects of the diffusion of a General Purpose Technology (GPT) that spreads first within the developed North country of its origin, and then to a developing South country. In the developed general equilibrium growth model, each final good can be produced by one of two technologies. Each technology is characterized by a specific labor complemented by a specific set of intermediate goods, which are enhanced periodically by Schumpeterian R&D activities. When quality reaches a threshold level, a GPT arises in one of the technologies and spreads first to the other technology within the North. Then, it propagates to the South, following a similar sequence. Since diffusion is not even, neither intra- nor inter-country, the GPT produces successive changes in the direction of technological knowledge and in inter- and intra-country wage inequality. Through this mechanism the different observed paths of wage inequality can be accommodated.

Keywords: North-South, general purpose technology, direction of technological knowledge, wage inequality
JEL Classification Codes: J31, F43, O31, O33

I. *Introduction*

Innovations of the general purpose technology (GPT) type — defined as innovations that

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have large, extensive and prolonged impacts on the economy, such as steam-engine, electricity and computers — typically take a long time to have a significant impact in the aggregate economy, as David (1990) documents for industrialized countries. Arguably, it takes even longer for the GPT to spread to developing countries, due to lower levels of technological knowledge. Therefore, this is certainly a case in which the process of GPT diffusion (transitional dynamics) is at least as relevant as its steady-state effects. In particular, wage inequality effects of technological change — that have been receiving ample analytical attention by authors such as Acemoglu (2002) and Dinopoulos and Segerstrom (1999) — generated throughout the long process are likely to play an important role in the GPT diffusion.

Major contributions to the literature on GPT using general equilibrium models (*e. g.*, Bresnahan and Trajtenberg,1995; Helpman and Trajtenberg, 1998; Petsas, 2003) have not dealt neither with international diffusion nor with wage inequality consequences, since they typically consider a closed-economy framework with a simplified productive structure with a single aggregate good and homogeneous labor. This paper extends the scope of the analysis by studying the wage-inequality effects of the diffusion of a GPT that spreads first within the developed country of its origin (North), and then to a developing country (South).

A general equilibrium model of Schumpeterian R&D with final goods produced by two substitute technologies is proposed. Each technology is characterized by a specific set of intermediate goods complemented by a specific labor — low- and high-skilled. The quality of intermediate goods is enhanced periodically in the North by innovations. When quality reaches a threshold level, a GPT arises in one of the technologies and spreads first to the other within the North. Then, it propagates to the South, following a similar sequence. Diffusion to the South, in the context of international trade of intermediate goods that embody technological knowledge, is achieved through imitative R&D.

In our framework the distinctive characteristic of the GPT innovation is its capacity of raising not only the productivity of the technology in which it has been generated, but also aggregate productivity in successive phases of the diffusion process. In this sense, the GPT works like an institutional improvement that permanently increases productivity. The role of institutional change in explaining changes in wage inequality has been stressed by Aghion *et al.* (2003). Thus, the analysis of the wage-inequality effects of the GPT, as defined in our framework, links the institutional explanation to the more common ones (see also Aghion *et al.,* 2003) related to technological change (*e.g.*, Acemoglu, 2002) and to international trade (*e.g.*, Wood, 1998). Through this link, the historical reality of the wage-inequality path in many developed and developing countries can be particularly accommodated.

The differentiated phases of the direction of technological knowledge, following the emergence of the GPT, determine different phases for the relative demand for each type of labor and, consequently, for the relative wage in both type of countries.

Many authors emphasize the causal relationship between the introduction (and diffusion) of a new GPT and the distribution of wages. For example, empirical evidence puts forward an increase in the skill premium in developed and developing countries during the 1980s and the early 1990s,[1] due to the introduction of computers (a new GPT). The title of Krueger's (1993)

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[1] For example, Machin and Van Reenen (1998) highlight the increase of the skill premium in the United States, the United Kingdom and Sweden between 1973 and 1989. The same path of the skill premium is illustrated by Berman *et al*. (1998) for ten developed economies during the 1980s.

paper on computers and wage inequality highlights this point of view: “How computers have changed the wage structure.” The same idea is shared by Greenwood and Yorukoglu (1997) and Caselli (1999). These authors draw attention to the occurrence of “technological revolutions” due to a “third industrial revolution”, which have positively affected the skill premium. Moreover, empirical evidence also indicates a decrease in the late 1990 and the early 2000s,[2] due to the end of the diffusion process.[3]

Earlier episodes in the twentieth century also support the view that the introduction of GPT innovations favor skilled workers. For example, concerning the 1910s, Goldin and Katz (1998, p. 695) argue that “the switch to electricity from steam and water-power energy sources was reinforcing because it reduced the demand for unskilled manual workers”. From the experience of the 1920s, Jerome (1934) considers that there is considerable reason to believe that radical (GPT) innovations raise the average skill required in the future.

In a scenario with lower openness to international trade and thus of greater independence among countries,[4] our framework also provides an explanation for the skill-replacing technological knowledge of the early nineteenth century in Britain (North country). In fact, the skill-replacing developments in English cities were dominated by the large increase in the supply of low-skilled labor, resulting from migration from villages and Ireland (*e.g.*, Habakkuk, 1962; Bairoch, 1988; Williamson, 1990), which made the introduction of these technologies profitable. Thus, contemporary historians (*e.g.*, quotations made by Habakkuk, 1962) considered the incentive to replace high-skilled artisans by low-skilled workers to be a major objective of technological-knowledge improvements of the period. In a context of our mechanism, by considering complementarity between inputs and substitutability between technologies in production, the increase in supply of low-skilled labor will have dominated the effect of the introduction (and diffusion) of new GPTs in production. As a result, the direction of technological knowledge has become skill replacing.

Thus, unlike the current main explanations for the path of wages, which, *ceteris paribus*, are unable to accommodate all the above occurrences, our framework is very flexible. The technological explanation (*e.g.*, Acemoglu, 2002) relies on the market size, *i.e.*, the observed high-skilled labor supply drives the direction of technological knowledge and wage inequality in favor of high-skilled workers. However, applied to increased trade with developing countries (low-skilled abundant), it would predict reduction of high-skilled technological-knowledge bias and, thus, of the skilled premium. Moreover, this literature contradicts the dominant literature on scale effects since Jones (1995a, b). In turn, the trade explanation (*e.g.*, Wood, 1998) depends on the Stolper-Samuelson theorem, *i.e.*, a decline in the relative price of the imported

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In case of developing countries, Zhu and Trefler (2005) observe an increase of the skill premium in Hong Kong, India, Thailand and Uruguay during the early 1990s. Avalos and Savvides (2006) report an increase in wage inequality in Latin America and East Asia between the mid 1970s and the mid 1990s. Brainerd (1998) finds evidence that the wage differential between the 90*th* and 10*th* wage percentiles widened in Russia during the first half of the 1990s.

[2] In case of developed countries, Nickell and Bell (1996) and Acemoglu (2003), for example, suggest a generic change in wage inequality in favor of low-skilled labor in the late 1990s.

In case of developing countries, Robertson (2004) detects that wage differential between the 90*th* and 10*th* wage percentiles decreased in Mexico between 1994 and 2004, and Zhu and Trefler (2005) show evidence that identical developments occurred in countries such as Bolivia, South Korea and Philippines.

[3] Some of all these findings are also confirmed by Juhn *et al*. (1993) and Card and DiNardo (2002), among others.

[4] Without relevant international trade, Northern results cease to be reflected in the South.

good must reduce the return of the factor that is used intensively in its production. However, applied to the developing country it would only predict a reduction of the skilled premium.

The paper is organized as follows. Section 2 defines the economic structure and the resulting international general equilibrium. Section 3 focuses, first, on the definition of the GPT and of its diffusion process and, then, simulates its implications for the path of intra and inter-country wage inequality. Some concluding remarks are presented in section 4.

II. *Economic Structure*

Each economy produces final goods in perfect competition and intermediate goods under monopolistic competition. R&D activities, when successful, result in innovations (in the North) and imitations (in the South) that are used by the intermediate-goods sector, as in Romer (1990). Labor and quality-adjusted intermediate goods are the inputs of final goods. The fraction of the aggregate final good that is not consumed is, in turn, used in the production of intermediate goods and in R&D.

1. Domestic Product and Factor Markets

Following Acemoglu and Zilibotti (2001) and Afonso (2006), each final good — indexed by $n \in [0, 1]$ — is produced by one of two substitute technologies — Low- and High-technology. Low (High)-technology combines, under constant returns to scale, low (high)-skilled labor, L (H), with Low (High)-specific intermediate goods indexed by $j \in [0, 1]$. The production function is:[5]

$$Y_n(t)=\begin{cases} A\left[\int_0^J \left(q^{k(j,t)}\, x_n(j,t)\right)^{1-\alpha} dj\right]\left[(1-n)\, L_n\right]^{\alpha} & if\ n\leq \bar{n}(t) \\ A\left[\int_J^1 \left(q^{k(j,t)}\, x_n(j,t)\right)^{1-\alpha} dj\right]\left(n\, h\, H_n\right)^{\alpha} & if\ n>\bar{n}(t) \end{cases}, \qquad (1)$$

A is the level of productivity, determined by the country's domestic institutions (exogenously) and by the state of general-purpose technology (endogenously). It is assumed that $A_S < A_N$ (S and N for South and North, respectively) is the only North-South difference in the parameters of the production function.

The integral terms are the contributions of quality-adjusted intermediate goods: x is the quantity, $q>1$ is the (exogenous) size of each quality improvement, $k(j, t)$ is the current quality rung in intermediate good j, and $1-\alpha$ is the aggregate intermediate-goods input share. In turn, $0<\alpha<1$ is the labor share and $h>1$ is an absolute advantage of high- over low-skilled labor;

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[5] Hence, the production function features complementarity between inputs — low (high)-skilled labor and Low (High)-specific intermediate goods — and substitutability between technologies — Low- and High-technology. Its flexibility is mainly useful for the analysis of causality from input levels to the direction of technological knowledge and, therefore, to wage inequality.

In particular, the combination of inputs in each technology — specific labor and specific quality-adjusted intermediate goods — under constant returns to scale is in line with other studies (*e.g.*, Acemoglu and Zilibotti, 2001; Afonso, 2006), since there is little empirical evidence of substantial decreasing/increasing returns (*e.g.*, Burnside *et al.*, 1995).

and the terms n and $1-n$ imply that L (H) has a comparative advantage in producing final goods indexed by small (large) ns.

This production function combines complementarity between inputs with substitutability between the two technologies. The optimal choice of technology is reflected in the equilibrium threshold $\bar{n}$, which results from profit maximization (by perfectly competitive final-goods producers and by intermediate-goods monopolists) and full-employment equilibrium in factor markets, given the supply of labor and the current state of technological knowledge,

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

$$\text{where } Q_L(t)\equiv\int_0^J q^{k(j,\,t)\left[\frac{1-\alpha}{\alpha}\right]}\,dj \text{ and } Q_H(t)\equiv\int_J^1 q^{k(j,\,t)\left[\frac{1-\alpha}{\alpha}\right]}\,dj \tag{3}$$

are aggregate quality indexes of the stocks of technological knowledge. The ratio $\frac{Q_H}{Q_L}$ is an appropriate measure of the technological-knowledge bias. Taking into consideration that the aggregate or composite final good (numeraire) is obtained by integration over final goods,[6]

$$Y(t)=\int_0^1 p_n(t)\;Y_n(t)\;dn=exp(-1)A^{\frac{1}{\alpha}}\left(\frac{1-\alpha}{q}\right)^{\frac{1-\alpha}{\alpha}}\left[(Q_L(t)L)^{\frac{1}{2}}+(Q_H(t)hH)^{\frac{1}{2}}\right]^2, \tag{4}$$

the threshold $\bar{n}$ can be implicitly expressed in terms of p_L and p_H, which are the price-indexes of Low and High final goods, respectively,

$$\frac{p_H(t)}{p_L(t)}=\left(\frac{\bar{n}(t)}{1-\bar{n}(t)}\right)^{\alpha}. \tag{5}$$

Full-employment in the labor market, implicit in $\bar{n}$, yields the following equilibrium skilled premium, measuring intra-country wage inequality:

$$\frac{w_H(t)}{w_L(t)}=\left(\frac{Q_H(t)\;h\;L}{Q_L(t)\;H}\right)^{\frac{1}{2}}, \tag{6}$$

where w_m is the wage per unit of m-type labor, $m=H, L$.

Together, equations (2), (5) and (6) are useful in foreseeing the operation of the price channel from the stocks (of labor and technological knowledge) to the flows of resources used in R&D and to wage inequality. For example, in a country relatively H-abundant and (or) with a large technological-knowledge bias, $\bar{n}$ is small, *i.e.,* many final goods are produced with the High technology and sold at a relatively low price. Profit opportunities in the production of intermediate-goods used by the relatively high-priced Low technology final goods induce a change in the direction of R&D against the technological-knowledge bias and in favor of low-skilled wages.

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[6] Thus, due to the terms n and $1-n$ in the production function (1), the composite final good (4) features constant elasticity of substitution between the two technologies Low and High (*e.g.*, Acemoglu and Zilibotti, 2001; Afonso, 2006).

2. R&D Technology

The results of successful R&D are innovations in the North and imitations in the South, owned and protected domestically, which improve the quality of intermediate goods and the stocks of technological knowledge, while creatively destroying the profits from the previous improvements (*e.g.*, Aghion and Howitt, 1992).

The probabilities of successful R&D are, in the North and South, respectively,

$$pb_N(k, j, t) = y_N(j, t)\cdot\beta_N\, q^{(\alpha-1)\alpha^{-1}k(j, t)}\cdot m_N(t)^{-\xi} \tag{7}$$

and

$$pb_S(k, j, t) = y_S(j, t)\cdot\beta_S\, q^{(\alpha-1)\alpha^{-1}k(j, t)}\tilde{Q}(t)\cdot m_S(t)^{-\xi}\cdot\tilde{Q}_m(t)^{-\sigma+\tilde{Q}_m(t)}, \tag{8}$$

where

(i) $y_i(j, t)$, $i = N, S$, is the flow of country i's final-good resources devoted to R&D in j;

(ii) $\beta_N\, q^{(\alpha-1)\alpha^{-1}k(j, t)}$, $\beta_N > 0$, is the North's net cost of the increasing complexity of quality improvements (net of the positive effect of accumulated public knowledge), as in Barro and Sala-i-Martin (2004, ch. 7); because the levels of accumulated public knowledge are different, this net cost in the South is adjusted by the relative m-specific technological knowledge of the South, defined as $\tilde{Q}_m(t) \equiv \dfrac{Q_{m,S}(t)}{Q_m(t)} \in]0, 1[$; in addition, $\beta_S > \beta_N$ means that the cost of complexity, for each k, is smaller in the case of imitation.

(iii) $m_i^{-\xi}$, $m = L, H$ and $\xi > 0$, is the adverse effect of market size, measured by the relevant labor, assuming, as suggested by Dinopoulos and Segerstrom (1999), that the costs of introducing new quality intermediate goods and replacing old ones are proportional to the size of the market.

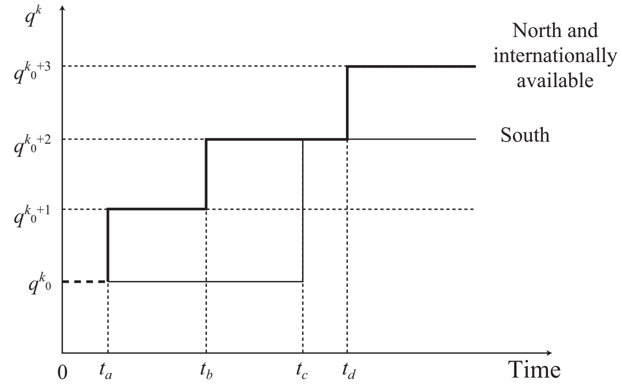
(iv) $\tilde{Q}_m(t)^{-\sigma+\tilde{Q}_m(t)}$, $\sigma > 0$, is a catching-up function, reflecting a decreasing advantage of technological-knowledge backwardness, as in Barro and Sala-i-Martin (1997); the size of σ affects how quickly the advantage of backwardness decreases with $\tilde{Q}_m$.

3. International Trade and Limit Pricing of Intermediate Goods

It is considered that the North and South freely trade intermediate goods only, while final goods and the other factors of production are internationally immobile. Resulting either directly from the latest innovation or indirectly through cheaper imitation of the latest innovation, internationally traded intermediate goods embody the state-of-the-art technological knowledge accumulated in the North, Q_m. This is the technological knowledge available to Southern producers of intermediate goods, which is higher than the South's domestic technological knowledge, $Q_{m,S}$, because at each point in time not all innovations have been imitated yet.

Following Grossman and Helpman (1991, ch. 12), it is assumed that limit pricing by each leading monopolist is optimal. And, in order to generate production and exports of some intermediate goods by the South, it is assumed that the marginal cost of producing final goods is lower in the South. As the aggregate final good is the input to the production of intermediate goods, the marginal cost advantage implies that when producing in the same quality rung, a

FIG. 1. PATH OF TECHNOLOGICAL-KNOWLEDGE IN THE INTERMEDIATE GOOD j



Southern producer is able to underprice its Northern competitor.

The dynamics of competitive advantage in each intermediate good depends crucially on the dynamics of innovations and imitations and, thus, it is endogenous. Figure 1 illustrates a possible path of the technological knowledge in an intermediate good. At t_a a Northern producer innovates, capturing the entire international market until t_b, when another Northern producer innovates and steals the entire business. At t_c a Southern producer imitates successfully, stealing, in turn, the entire business (due to the marginal cost advantage prevailing in the South) until the next innovation occurs at t_d. In this particular intermediate good, between t_c and t_d, the South's domestic technological knowledge equals the technological knowledge internationally available, while between t_a and t_c and after t_d it is smaller.

Due to the different levels of productivity, international immobility of labor and the limited substitutability between the two types of labor (owing to the complementarity with sets of intermediate goods), international trade is not sufficient to equalize wages neither intra- nor inter-country.

As for intra-country differences in wages, equation (6) applied to the North and South with trade of intermediate goods shows that relative wages depend on relative labor endowments. Assuming that the North is relatively H abundant, *i.e.*,

$$\frac{H_N}{L_N} > \frac{H_S}{L_S}, \tag{9}$$

the following inequality holds:[7]

$$\frac{w_{H,N}}{w_{L,N}} = \left(\frac{Q_H\, h\, L_N}{Q_L\, H_N}\right)^{\frac{1}{2}} < \frac{w_{H,S}}{w_{L,S}} = \left(\frac{Q_H\, h\, L_S}{Q_L\, H_S}\right)^{\frac{1}{2}}. \tag{10}$$

Inter-country wage inequality, in turn, depends crucially on exogenous productivity

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[7] Note that since in autarky the relevant technological knowledge is the domestic one instead of the internationally available, the South's wage premium under autarky $\left.\frac{w_{H,S}}{w_{L,S}}\right|_{pre-trade} = \left(\frac{Q_{H,S}\, h\, L_S}{Q_{L,S}\, H_S}\right)^{\frac{1}{2}}$ differs from the one in equation (10).

differences,

$$\frac{w_{m,S}}{w_{m,N}}=\left(\frac{p_{m,S}\,A_S}{p_{m,N}\,A_N}\right)^{\frac{1}{\alpha}}. \tag{11}$$

Wages are lower in the South if, as assumed, $A_S < A_N$ and differences in prices of final goods are of second order.

4. General Equilibrium

The equilibrium relationships for given states of aggregate resources allocation, technological knowledge and labor are derived above. For labor is assumed, as a baseline, constant exogenous endowments according to (9).

Concerning technological knowledge, its accumulation is largely driven by both probabilities of successful R&D. Following Grossman and Helpman (1991), the incentive to invest in R&D relies on the expected amount of profits, which depend directly on the probability of success and indirectly on the probability of success by the competitors. For example, the current value that a monopolist producer of intermediate good j in the South attaches to a domestically patented imitation of the state-of-the-art quality is given by:

$$V_S(k,j,t)=\frac{\Pi_S(k,j,t)}{r_S(t)+pb_N(k,j,t)}, \tag{12}$$

where Π is the monopolist's instantaneous profit and r is the market interest rate. The presence of $pb_N(k,j,t)$ in the expression occurs because the expected duration of profits for the Southern monopolist competing in the international market depends on the probability of a successful innovation (in the North). This example corresponds to the period between t_c and t_d in Figure 1, above. In general, even though patents are non-tradable internationally, trade of intermediate goods alone establishes the interaction between R&D activities in the North and South.

Since intermediate goods are demanded by producers of final goods in both countries, monopolist's profits are sensitive to the size of both markets. Due to complementarity, market size is appropriately measured by the specific labor; for instance, the profits at time t of a Southern monopolist producer of a H-specific intermediate good are

$$\begin{aligned}\Pi_{H,S}(k,j,t)=h(1-\alpha)^{\alpha^{-1}}q^{k(j,t)\,(1-\alpha)\alpha^{-1}}(1-MC_S)\cdot&\\ \cdot\{H_S\,[A_S\,p_{H,S}(t)]^{\alpha^{-1}}+H_N\,[A_N\,p_{H,N}(t)]^{\alpha^{-1}}\},&\end{aligned} \tag{13}$$

where $MC_S < 1$ is the exogenous marginal cost of final goods in the South.

The positive influence of the market size on profits, and thus on R&D incentives, contrasts with its adverse effect through the increasing cost of introducing new goods in the market, as defined above in (7 and 8)-(iii): the first effect dominates if $\xi < 1$, implying a bias in R&D in favor of the more abundant type of labor; whereas the two effects cancel each other out when $\xi = 1$ and, in this last case, scale effects are negligible and, therefore, the bias mechanism relies only on the price channel.

The demand-side allocation of aggregate resources, between consumption and savings, closes the general equilibrium determination: consumers split the aggregate final good into consumption and savings, which, in turn, are allocated between production of intermediate goods and R&D. Thus, savings consist of accumulation of financial assets, with return r, in the form of ownership (non-tradable internationally) of the firms that produce intermediate goods. The value of these firms, in turn, is determined by the value of patents in use. For simplicity it is considered that consumption-savings choices are independent of individuals' skills (low or high) and country. Therefore, considering a constant intertemporal elasticity of substitution (CIES) instantaneous utility function, the consumption path optimally chosen by the single representative individual is given by the Euler equation

$$\frac{\dot{c}(t)}{c(t)} = \frac{r(t) - \rho}{\theta}, \tag{14}$$

where $\theta > 0$ is the constant elasticity of intertemporal substitution and $\rho > 0$ is the constant discount rate of utility.

The dynamic general equilibrium resulting from optimal decentralized behavior can be described by the path of the state of both types of domestic technological knowledge towards the steady state. The full solution requires numerical methods, which are used to describe, below, the dynamics following a GPT (baseline parameter values and initial conditions are in the appendix). However, in particular, the steady-state growth rate, g^* (assumed positive), common to both types of technological knowledge and to both countries,

$$g^* = \frac{\dot{Q}_m}{Q_m}^{*} = \frac{\dot{Q}_{m,S}}{Q_{m,S}}^{*} = \frac{r^* - \rho}{\theta}, \tag{15}$$

can be derived analytically. The steady state given by (15) implies constant technological-knowledge bias and constant inter-country gaps. During transition to the steady state, though, interest rates and technological-knowledge growth differ between countries, since assets are non-tradable internationally.

III. *The Path and Consequences of a GPT*

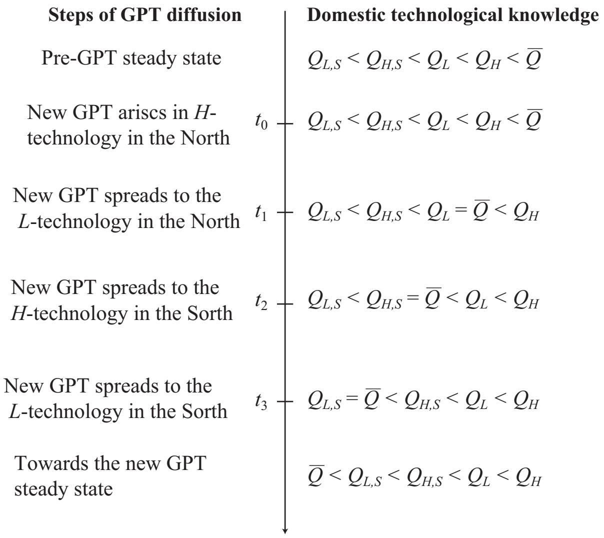
The genesis of a GPT is modeled as a particular innovation in one of the Northern final-goods technologies. This innovation is manifested as a positive permanent shock to exogenous productivity not only of that particular technology but also of the entire economy. Part of the additional resources available after that shock increase investment in R&D thereby accelerating the spread of the GPT, first to the other technology in the North an then to the South. During this process the direction of technological knowledge changes, affecting wage inequality.

1. Genesis and Diffusion of a GPT

The innovation that triggers the shock in productivity arises in one of the final-goods technologies in the North when the respective aggregate quality index — Q_m — endogenously reaches an exogenous threshold $\overline{Q}$. In the steady-state path, according to (15), both Qs are growing at the same positive rate, hence both are able to eventually reach $\overline{Q}$. It is assumed that

$$Q^*_H(t) > Q^*_L(t) > Q^*_{H,S}(t) > Q^*_{L,S}(t), \tag{16}$$

FIG. 2. GPT DIFFUSION AND DOMESTIC TECHNOLOGICAL KNOWLEDGE



so that the threshold is first reached by the H-technology in the North and so on, as described in Figure 2.

Each shock in productivity — $\varepsilon > 0$ —, (i) temporarily affects the absolute advantage of the type of labor that complements the specific technology in which the GPT arises and (ii) shifts A permanently, in accordance to its general purpose character. In line with the sequence in Figure 2, the following definitions, referring to parameters in the production function (1) are useful:

$$\text{in the North: } \begin{cases} \ln \overline{h} = \ln h + \varepsilon & \textit{if } Q_L < \overline{Q} \leqslant Q_H \\ \ln h & \textit{otherwise} \end{cases} \tag{17}$$

$$\text{in the South: } \begin{cases} \ln \overline{h} = \ln h + \varepsilon & \textit{if } Q_{L,S} < \overline{Q} \leqslant Q_{H,S} \\ \ln h & \textit{otherwise} \end{cases}$$

$$\text{in the North: } \begin{cases} \ln A_N & \textit{if } Q_H < \overline{Q} \\ \ln \overline{A}_N = \ln A_N + \varepsilon & \textit{if } Q_L < \overline{Q} \leqslant Q_H \\ \ln \overline{\overline{A}}_N = \ln \overline{A}_N + \varepsilon & \textit{if } Q_L \geqslant \overline{Q} \end{cases} \tag{18}$$

$$\text{in the South: } \begin{cases} \ln A_S & \textit{if } Q_{H,S} < \overline{Q} \\ \ln \overline{A}_S = \ln A_S + \varepsilon & \textit{if } Q_{L,S} < \overline{Q} \leqslant Q_{H,S} \\ \ln \overline{\overline{A}}_S = \ln \overline{A}_S + \varepsilon & \textit{if } Q_{L,S} \geqslant \overline{Q} \end{cases}$$

Improvements in productivity at t_0, when Q_H reaches $\overline{Q}$, release resources that become

TABLE 1. QUALITATIVE GROWTH OF AGGREGATE QUALITY INDEXES

	$\frac{\dot{Q}_H}{Q_H}$		$\frac{\dot{Q}_L}{Q_L}$		$\frac{\dot{Q}_{H,S}}{Q_{H,S}}$		$\frac{\dot{Q}_{L,S}}{Q_{L,S}}$
Before t_0	g_0^*	$=$	g_0^*	$=$	g_0^*	$=$	g_0^*
t_0	$\Big\uparrow$		$\big\uparrow$		$\uparrow$		$\scriptstyle\uparrow$
t_1	$\big\uparrow$		$\Big\uparrow$		$\scriptstyle\uparrow$		$\uparrow$
t_2	$\uparrow$		$\scriptstyle\uparrow$		$\Big\uparrow$		$\big\uparrow$
After t_3	$\scriptstyle\uparrow$		$\uparrow$		$\big\uparrow$		$\Big\uparrow$
New steady state	g_1^*	$=$	g_1^*	$=$	g_1^*	$=$	$g_1^* > g_0^*$

partly available to investment in R&D activities directed to both technologies, thereby increasing probabilities of success, which accelerates not only Q_H but also Q_L, bringing forward t_1. In turn, these higher aggregate quality (or technological knowledge) indexes, available internationally through trade, benefit the South, also from the outset (even before t_2), through a similar mechanism. Indeed, higher Northern aggregate quality indexes improve productivity, releasing resources for imitative R&D, and thereby accelerating domestic technological knowledge. Consequently, the acceleration brings forward the introduction of the GPT at t_2 and then t_3.

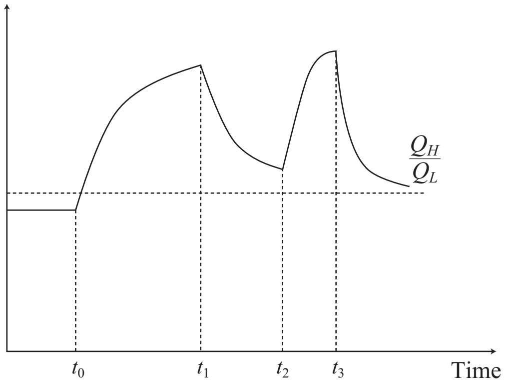
The process of GPT emergence and diffusion using numerical computation of transitional dynamics is simulated with the calibration presented in the appendix. Table 1 depicts, qualitatively, the changes in the growth of the technological knowledge indexes over the entire period of diffusion of the GPT. Starting from a steady state, with growth according to (15), the differentiated growth rates following the new GPT depend on the phase of the diffusion process.

The larger arrow in the growth of Q_H between t_0 and t_1 means that the resources released by the improvements in productivity in the North ($\bar{h} > h$ and $\bar{A}_N > A_N$) are asymmetrically allocated in R&D. In fact, due to the temporary increase in the absolute advantage of high-skilled labor ($\bar{h} > h$), profits of the complementary intermediate-goods producers increase more, thereby stimulating allocation of resources to H-specific R&D. As a result, the probability of successful H-specific innovations increases. After t_1, once the GPT spreads within the North, the temporary increase in h vanishes, reverting the allocation bias, while more resources are released by a new increase in overall productivity ($\bar{\bar{A}}_N > \bar{A}_N$).

As long as the GPT does not spread into the South, the correspondent arrows are smaller, while asymmetry comes from the differentiated catching-up magnitudes — the advantage of backwardness becomes relatively stronger first in High and then in Low technological knowledge. Then, when the GPT spreads internationally (at t_2 and t_3), the differences in growth rates revert in favor of the South through the same type of mechanisms experienced by the North at t_0 and t_1. However, growth in the North still benefits from the increases in Southern productivity: the positive effect that higher demand (by Southern final-goods producers) for intermediate goods has on innovations more than offsets the business-stealing effect of increased imitation.

At the end of the process of diffusion of the GPT, after the transitional dynamics to the new steady state, the resulting world growth rate has been enhanced by the successive productivity improvements. From (15), it is clear that this higher steady-state growth rate reflects a higher interest rate, which corresponds to a higher return from assets (patents in use)

FIG. 3. TECHNOLOGICAL-KNOWLEDGE GAP



that have become more valuable.

2. Implications on the Direction of Technological Knowledge and Wage Inequality

The differentiated changes in growth qualitatively described in table 1 result in differentiated phases of the direction of technological knowledge following the emergence of the GPT, as shown in Figure 3.[8] At the end of the diffusion process the temporarily higher absolute advantage of the technology where the GPT first emerges generates a permanent bias: the direction of the new steady-state technological knowledge is *H*-biased relatively to the pre-GPT steady state.

Due to complementarity of inputs in the production of final goods (1), the direction of technological knowledge, together with the changes in productivity, determines the relative demand for each type of labor and, consequently, the relative wage in each country.

Plugging the changes in the absolute advantage of high-skilled labor — as defined in (18) — into the equilibrium equation (6), above, the level of the high-skilled premium jumps upwards at t_0 in the North and at t_2 in the South and downwards at t_1 and t_3. In turn, the high-skilled premium growth, with constant labor endowments, depends exclusively on the growth of the technological-knowledge bias,

$$g_{\frac{w_{H,N}}{w_{L,N}}}=g_{\frac{w_{H,S}}{w_{L,S}}}=\frac{1}{2}g_{\frac{Q_H}{Q_L}}. \tag{19}$$

This mechanism, through which the emergence and diffusion of the GPT influence intra-country wage inequality, generates the phases on the bottom graph of Figure 4. Notably, under international trade, whereas the succession of jumps depends on the timings of domestic diffusion, the growth of relative wages in the South is fully affected at the time of emergence of the GPT in the North.

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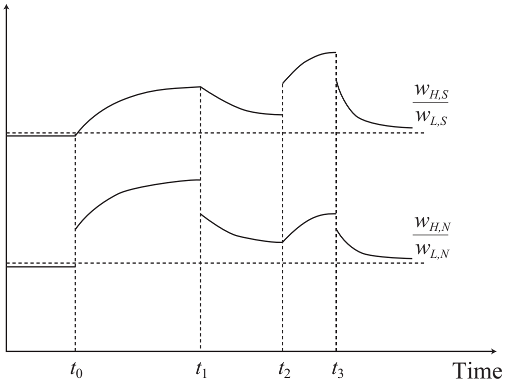
[8] Recall that with free trade of intermediate goods the technological knowledge embodied in intermediate goods used in both countries is Q_L and Q_H, even though the domestic levels $Q_{L,S}$ and $Q_{H,S}$ are relevant for the timing of GPT adoption in the South.

FIG. 4. INTRA-COUNTRY WAGE INEQUALITY



The recent and early twentieth-century evidence on intra-country wage inequality can indeed be accommodated by the proposed mechanism:

- Following the introduction and diffusion of computers (a new GPT), the empirical evidence detects an increase in the skill premium in developed countries (*e.g.*, Machin and Van Reenen, 1998; Berman *et al.*, 1998) and in developing countries (*e.g.*, Zhu and Trefler, 2005; Avalos and Savvides, 2006), during the 1980s and the early 1990s. Furthermore, in line with the end of the diffusion process, empirical evidence also indicates a decrease in developed countries (*e. g.*, Nickell and Bell, 1996; Acemoglu, 2003) and in developing countries (*e.g.*, Robertson, 2004; Zhu and Trefler, 2005).
- Earlier episodes in the twentieth-century also support the view that the introduction and diffusion of GPT innovations favor skilled workers — *e.g.*, Goldin and Katz (1998), for the effect of the electricity in the 1910s.

Moreover, our framework also provides an explanation for the skill-replacing technological knowledge of the early nineteenth-century in (North) Britain:[9] low-skilled labor in factories replaced skilled artisans (high-skilled labor). During this century, radical technological-knowledge improvements have been concomitant with a large increase in the supply of low-skilled labor, resulting from migration from villages and Ireland (*e. g.*, Habakkuk, 1962; Bairoch, 1988; Williamson, 1990). The increase in supply of low-skilled labor, L, dominated the effect of the introduction (and diffusion) of new GPTs, which starts by affecting h in production. Consequently, in our model with complementarity between inputs and substitutability between technologies, the higher increase in L compared with the increase in h has affected the direction of the technological knowledge such that the relative demand for low-skilled labor has increased.[10]

Still on the analysis of intra-country wage inequality, the direct effect of recent changes in institutional features on wages is explicitly omitted:[11] thus, it is implicitly assumed that this

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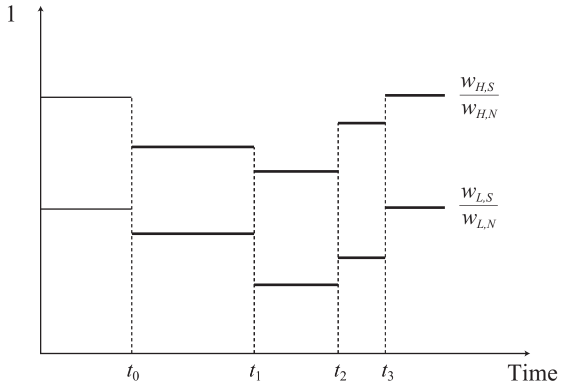
[9] Without relevant international trade, the results in the Northern (Britain) country cease to be reflected in Southern countries.

[10] In technical terms, it is as if, *ceteris paribus*, in relative terms h had decreased.

FIG. 5. INTER-COUNTRY WAGE INEQUALITY



effect is limited. In turn, institutional features can also be reflected in the absolute advantage of high over low-skilled labor in production. As a result, in our framework, changes in institutional features affect the path of technological knowledge (demand of labor and wages) through the same channel as the use of a new GPT.

Since international trade equalizes the growth of relative wages, the changes in inter-country wage inequality along the process of diffusion, depicted in Figure 5, are determined only by the GPT productivity shocks defined above in (17) and (18). The transmission of those shocks to inter-country relative wages is derived from the conjunction of equilibrium equations (2), (5) and (11): the latter shows how inter-country wage inequality depends on the relative overall productivity (A_S/A_N) and on relative prices of final goods; (5) shows that the prices of final goods, in turn, depend on the threshold final good; and, finally, (2) indicates that the threshold final good in each country changes with h. At t_0, for example, both high and low-skilled relative inter-country wages are affected by the increase in the relative overall productivity in the North ($A_S/\overline{A}_N<A_S/A_N$) and the high-skilled relative wage is, in addition, affected by the temporary increase in h in the North.

IV. *Concluding Remarks*

A process of emergence and intra- and inter-country diffusion of a new GPT has been simulated in a dynamic general-equilibrium framework where growth is driven by Schumpeterian-R&D applied to intermediate goods that complement either high- or low-skilled labor in the production of final goods. A crucial result of this complementarity is that the direction of technological knowledge determines the path of intra-country wage inequality. Under free trade of intermediate goods, this result applies internationally.

In particular, two stylized countries, one (North, where R&D is innovative and skilled-

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[11] In particular, changes in labor market institutions (*e.g.*, labor market unions) and in organizational change, which may have decreased the wages of low-skilled workers (*e.g.*, Freeman, 1991; DiNardo *et al.*, 1995; Lee, 1999; Kremer and Maskin, 1999; Autor *et al.*, 2003).

labor is relatively abundant) more developed than the other (South, where R&D is imitative), are considered. The GPT is modeled as a particular innovation in the North that is a positive permanent shock to the productivity not only of that particular technology but also of the entire economy. Additional resources available after that shock increase investment in R&D thereby accelerating, from the outset, the spread of the GPT to other technologies, first in the North an then in the South. During the diffusion process the direction of technological knowledge changes successively, affecting wage inequality. If the GPT emerges in a high-skilled technology, the relative demand for high-skilled labor increases, raising the high-skilled premium until the GPT starts spreading to the other technologies.

Since under trade of intermediate goods the direction of technological knowledge that prevails internationally results from innovative R&D, the growth of relative wages in the South is fully affected from the outset (at the time of emergence of the GPT in the North), whereas there are successive discrete changes in levels that depend on the timings of domestic diffusion.

Hence, the path of the technological-knowledge bias, following the emergence of the GPT, determines different phases for the skill premium in both type of countries. These phases are able to accommodate the historical reality of the wage-inequality path in many developed and developing countries.

In the baseline calibration used, scale effects have been eliminated in favor of the price-channel mechanism. However, the use of our model, which allows for simultaneous scale and price effects, in future research should be able to assess the strength of the market-size channel *versus* price channel.

Further details of the most recent fall in wages of low-skilled labor — namely in developing countries — provide another promising extension for this research. This discussion would have to consider detailed institutional features. In particular, it would be necessary to explicitly consider the observed changes in labor market institutions (*e.g.*, labor market unions) over the past three decades. These changes may have decreased the wages of low-skilled workers (*e. g.*, Freeman, 1991; DiNardo *et al.*, 1995; Lee, 1999). Moreover, it would be necessary to explicitly consider the observed transformations in firms' organizational change, or maybe in the way that firms and workers match (*e.g.*, Kremer and Maskin, 1999; Autor *et al.*, 2003). Implicitly, by omitting detailed institutional features, we consider that their direct effect on wages is limited and we conjecture that, such as the emergence of a GPT, their effect on wages is reflected in the absolute advantage of high over low-skilled labor and, through this channel, affects path of technological knowledge (demand of labor and wages).

APPENDIX: Baseline Parameter Calibration

TABLE 2. BASELINE PARAMETER VALUES AND INITIAL CONDITIONS

Parameter	Value	Parameter	Value	Parameter	Value
A_N	1.50	σ	1.50	$\overline{Q}$	1.20
A_S	1.00	θ	1.05	H_N	1.30
α	0.60	ρ	0.03	H_S	0.45
h	1.20	$\tilde{Q}_H(0)$	0.79	L_N	1.00
MC_S	0.80	$\tilde{Q}_L(0)$	0.66	L_S	0.55
β_N	0.40	$Q_H(0)$	1.11	ε	0.10
β_S	0.80	$Q_L(0)$	1.00	ξ	1.00

Baseline parameter calibration follows our previous related work — Afonso (2006) — and initial levels are set according to condition (9) and to pre-GPT steady-state equilibrium.

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