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Innovation, Industrial Dynamics and Economic Growth

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Abstract

We present a class of dynamic general-equilibrium models of education, innovation and technology transfer to explain the evolution of industries and aggregate growth in closed and open economies. Firms employ educated workers in order to develop higher-quality products. The realization of quality innovations becomes more difficult as the quality level increases but this deterioration of technological opportunities is compensated by an improvement of the researchers' capabilities. Innovation and human-capital accumulation appear as in-line engines of scale-invariant endogenous growth. Industries evolve according to stochastic processes of innovation, imitation and technology adaption in the global economy.

Keywords: Education, innovation, industrial dynamics, technology transfer, international trade, economic growth

JEL Classification: F43, O31, O33, O34

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1 Introduction

Today it is widely accepted that education and innovation are the two most important engines of per-capita economic growth. In his pioneering contribution to the New Growth Theory, Lucas (1988) has emphasized the accumulation of workers' human-capital by education as a decisive source of endogenous growth. Empirical work by Hanushek and Kimko (2000), Barro (2001), and Hanushek and Wößmann (2008) has confirmed that the quantity and even more the quality of schooling and education are positively related to economic growth. Since the early nineties, however, endogenous growth theory is dominated by R&D-based growth models where innovation dynamics serve as engine of growth. Romer (1990), Grossman (1990), Grossman and Helpman (1991a) and Aghion and Howitt (1992, 1998, 2005) have been the first to explain long-run per-capita growth by intentional R&D activities of private firms. According to these first-generation R&D-based growth models, technological change results either from an endless sequence of vertical improvements of consumer or intermediate goods or from a continuing horizontal expansion of the variety of goods.

The R&D-based growth models of the first generation share a common property which is well-known as the "scale effect". This effect predicts that larger economies grow faster and that population growth causes increasing per-capita growth rates. The counterfactual result of increasing growth rates persists when unskilled labor is replaced by skilled labor and population growth is replaced by human-capital growth. For this reason, no successful attempts have been made to integrate the Lucas (1988) mechanism of human-capital accumulation into the first-generation R&D-based growth models. Instead, education on the one hand and innovation on the other have been treated as two alternative and independent engines of economic growth (see, e.g., Barro and Sala-i-Martin 2004).

In the mid-nineties, Jones (1995a) has presented an influential empirical study on the scale effect. In response to the expressed "Jones critique", a new class of semi-endogenous growth models has emerged (see, e.g., Jones 1995b, 2002, Kortum 1997, Segerstrom 1998). As a distinguishing feature, these second-generation R&D-based growth models remove the scale effect by the assumption that the difficulty of R&D increases over time, and instead imply that per-capita growth depends proportionally on the exogenously given population growth rate. As a consequence, constant population leads to an equilibrium characterized by a steady state without innovation and growth dynamics. We do not share this pessimistic view on technological progress in the future. Our assessment is in line with the empirical evidence which is certainly not in favor of the semi-endogenous growth models (see, e.g., the discussion in Zachariadis 2003, Laincz and Peretto 2006, Ha and Howitt 2007, Madsen 2008, and Venturini 2012). Thus, theoretical and empirical reasons lead us refrain from the semi-endogenous growth theory. Instead, we prefer the scale-invariant, fully endogenous R&D-based growth models of the third and newest generation.[1] As in the semi-endogenous growth theory, the scale effect is removed by an increasing difficulty of R&D, but this deterioration of technological opportunities is compensated by a continuous improvement of researchers' human capital.

This paper takes into account the close interplay of education and innovation in driving economic growth. Some promising attempts in this direction have been made. Arnold (1998) and Blackburn, Hung and Pozzolo (2000) have integrated education in Romer's (1990) variety-expansion model, whereas Arnold (2002), Stadler (2003, 2012, 2013), Strulik (2005), and Chu et al. (2013) have incorporated education and skill acquisition in the quality-upgrading model of Grossman and Helpman (1991a,b). Since we are interested in the stochastic dynamics of innovation, technology transfer and industrial development, we restrict our analysis to the quality-ladder approach of the Schumpeterian growth theory which associates innovation and growth with a process of creative destruction, as was emphasized by Schumpeter (1942).

Of course, the theoretical analysis of R&D-based growth is not restricted to closed economies. Earlier work has already combined quality-ladder models of all three generations with the New Trade Theory which builds heavily on the theory of Industrial Organization. To mention just a few examples, Grossman and Helpman (1990, 1991a) have integrated their first-generation R&D-based growth model into the traditional framework of international trade. Among several other studies, Dinopoulos and Segerstrom (2007, 2010) have analyzed North-South trade and international product cycles within various semi-endogenous growth models of the second generation. Stadler (2007) has modified this intriguing class of North-South trade models by replacing exogenous population growth by endogenous human-capital accumulation. This reformulation defines his model as Schumpeterian growth model of the

[1]The basic structure of the alternative versions of fully endogenous growth models of the third generation is presented in Jones (1999).

third generation. Accordingly, the present paper extends the analysis to a class of unified general-equilibrium models of education, innovation and technology transfer in the global economy in order to explain the dynamics of industrial development and aggregate growth.

The remainder of the paper is organized as follows. Section 2 presents a basic model of education and innovation in a closed economy. We derive the balanced path of endogenous scale-invariant growth and show that fundamental scientific discoveries will inevitably induce innovation clusters across industries imposing aggregate growth cycles. Section 3 opens the economy and analyzes international product cycles with quality innovations realized by firms in the developed North and imitations realized by firms in the developing South. This allows us to analyze the dynamics of international technology transfer by imitation. Section 4 studies an alternative channel of technology transfer from North to South via foreign direct investment by multinational firms. We compare the complementary models with respect to the influence of globalization and the strength of protection of intellectual property rights. Section 5 summarizes and concludes.

2 Education, Innovation and Growth

According to the latest generation of scale-invariant growth models we consider an economy consisting of a continuum of firms, each producing a differentiated consumer good. The goods are sold to households who have preferences for quantity and quality. Each household is endowed with one unit of (raw) labor and can increase skills by accumulating its human capital.

Education and Consumer Spending

Households share identical preferences and maximize their discounted utility

$$U(C) = \int_0^\infty e^{-\rho t} \ln C \; dt \, , \tag{2.1}$$

where $\rho > 0$ is the constant discount rate and

$$C = \left[\int_0^1 \phi(j)^{1-\alpha} q(j)^\alpha \; dj \right]^{1/\alpha} , \quad 0 < \alpha < 1 \tag{2.2}$$

is a quality-augmented Dixit-Stiglitz consumption index which measures instantaneous utility. It reflects the households' preferences for quantity $q(j)$ and quality $\phi(j)$ of the demanded products available from a continuum of industries j indexed on the unit interval $[0,1]$.[2] According to these preferences, the elasticity of substitution between any two products across industries is given by $1/(1-\alpha)$.

Utility maximization follows two steps. First, the across-industry optimization problem is solved at each point in time. Maximizing the consumption index (2.2) subject to the budget constraint

$$I = \int_0^1 p(j)q(j)\, dj \ ,$$

where I denotes consumer spending and $p(j)$ is the price of product j, yields the individual consumer's demand functions

$$q(j) = \frac{\phi(j)p(j)^{-\frac{1}{1-\alpha}} I}{\int_0^1 \phi(j)p(j)^{-\frac{\alpha}{1-\alpha}}\, dj} \tag{2.3}$$

for all products $j \in [0,1]$. The consumption index (2.2) can then be rewritten as

$$C = I/P_C \ , \tag{2.4}$$

where $P_C \equiv \left[\int_0^1 \phi(j)p(j)^{-\frac{\alpha}{1-\alpha}}\, dj\right]^{-\frac{1-\alpha}{\alpha}}$ is the quality-adjusted price index of consumer goods.

Second, the dynamic optimization problem is solved by maximizing the individual consumer's discounted utility. Households supply human capital H to production, R&D, and education. By devoting the share θ of human capital to work in the production and research sectors, they face the dynamic budget constraint

$$\dot{A} = rA + w\theta H - I \ , \tag{2.5}$$

where A denotes the value of a household's asset holdings, r is the interest rate and w is the wage rate for each unit of human capital which is normalized to $w = 1$.

[2]This specification of the consumption index is widely used in the R&D-based growth literature (see, e.g., Thompson and Waldo 1994, Dinopoulos and Thompson 1998, Li 2001, 2003, and Segerstrom 2007).

By devoting the remaining share $(1-\theta)$ of human capital to education, households raise their human capital according to the Uzawa-Lucas technology

$$\dot{H} = \kappa(1-\theta)H - \delta H \ , \tag{2.6}$$

where $\kappa(> \delta + \rho)$ denotes the effectiveness of the educational system and δ is the constant depreciation rate of human capital. Thus, each household maximizes its discounted utility (2.1), given (2.4), subject to the dynamic budget constraint (2.5) and the accumulation function (2.6).

The current-value Hamiltonian of this control problem is given by

$$\mathscr{H} = \ln I - \ln P_C + \psi_1[rA + \theta H - I] + \psi_2[(\kappa(1-\theta) - \delta)H]$$

where ψ_1 and ψ_2 are the costate variables of the states A and H, respectively. The necessary first-order conditions are

$$\mathscr{H}_I = 1/I - \psi_1 = 0 \ , \tag{2.7}$$

$$\mathscr{H}_A = \psi_1 r = \psi_1 \rho - \dot{\psi}_1 \ , \tag{2.8}$$

$$\mathscr{H}_\theta = \psi_1 H - \psi_2 \kappa H = 0 \ , \tag{2.9}$$

$$\mathscr{H}_H = \psi_1 \theta + \psi_2(\kappa(1-\theta) - \delta) = \psi_2 \rho - \dot{\psi}_2 \ . \tag{2.10}$$

Conditions (2.7) and (2.8) lead to the Keynes-Ramsey rule

$$\dot{I}/I = r - \rho \ ,$$

which explains the growth rate of consumer spending by the difference between the interest rate and the discount rate. Further, we derive from (2.9) and (2.10) the costates' growth rates

$$\dot{\psi}_1/\psi_1 = \dot{\psi}_2/\psi_2 = -(\kappa - \delta - \rho)$$

and hence from (2.8) the interest rate

$$r = \kappa - \delta \ , \tag{2.11}$$

such that the Keynes-Ramsey rule can be expressed as

$$\dot{I}/I = \kappa - \delta - \rho \,. \tag{2.12}$$

The larger the effectiveness of education κ and the lower the depreciation and discount rates δ and ρ, the larger is the growth rate of consumer spending.[3]

The Product Markets

In each industry, the products' quality grades are arrayed along the equidistant rungs of a quality ladder which is assumed to be equal across industries.[4] Each new generation of products provides a quality level, λ times higher than the previous one, where the upgrading factor $\lambda > 1$ is exogenously given.

The quality level of the top-of-the-line product in industry j is

$$\phi(j) = \tilde{\lambda}^{m(j)} \,, \tag{2.13}$$

where $\tilde{\lambda} = \lambda^{\alpha/(1-\alpha)}$ is an alternative measure of innovation size and $m(j)$ is the number of sequential upgrading innovations in industry j up to the present time.

All existing consumer goods are produced subject to a constant returns to scale technology with skilled labor as the single input. There is a fixed mass L of households which supply human-capital in exchange for wage payments. One unit of skill-adjusted labor, LH, produces one unit of output, regardless of the quality level. Therefore, each firm has a constant marginal cost which is equal to the wage rate $w = 1$, and the supplier of the highest quality of variety j maximizes the flow of profits

$$\pi(j) = (p(j) - 1)q(j)L \,.$$

The price-setting behavior of a quality leader depends on the underlying industry structure which in turn depends on the technological conditions. In the present paper, we restrict our analysis to the case of drastic innovations such that the quality

[3] For an analysis of the impact of education subsidies, see, e.g., Stadler (2012).

[4] An extension of the presented model allowing for different distances of the rungs within and across industries is analyzed in Stadler (2013), where the distances are Pareto-distributed as suggested by Minniti, Parello and Segerstrom (2013).

leaders find it optimal to charge monopoly prices. The constant price elasticity of demand, $-1/(1-\alpha)$, implies monopolistic competition at prices $p(j) = p = 1/\alpha < \lambda$, being equal across all industries.[5]

Since all quality leaders charge identical prices, we obtain from (2.3) a firm's demand function

$$Q(j) = \alpha IL\phi(j)/\Phi \ , \tag{2.14}$$

where $\Phi = \int_0^1 \phi(j)\ dj$ is the average quality of all products currently produced by the incumbent firms. All quality leaders realize the flow of profit

$$\pi(j) = (1-\alpha)IL\phi(j)/\Phi \ , \tag{2.15}$$

which differs across industries with respect to the relative quality level $\phi(j)/\Phi$. This heterogeneity provides an incentive for challengers to engage in R&D activities in the most progressive industries.

Innovation Dynamics

The quality of consumer goods is upgraded by a sequence of product innovations, each building on its predecessors. The opportunity of realizing profits drives potential entrants to engage in risky R&D projects in order to develop higher-quality products. The first firm to succeed in developing the next higher-quality product in an industry is granted an infinitely-lived patent for the new technology. Competition therefore takes the form of an endless sequence of patent races between an arbitrary number of challenger firms.[6] Any quality innovation opens up the opportunity for all challenger firms to search for the next higher quality innovation in this industry. This reflects an external spillover effect of technological knowledge since even laggard firms can equally participate in each patent race without having climbed all of the rungs of the quality ladder themselves. Every firm may target its research efforts at any of the continuum of state-of-the-art products, i.e., it may engage in any industry. If a

[5]In case of non-drastic innovations, the leading firms find it optimal to charge the limit price $p = \lambda = \tilde{\lambda}^{(1-\alpha)/\alpha}$. When innovation sizes are random, both types of price-setting behavior occur in different industries at the same time.

[6]It can be shown that incumbent firms have no incentive to engage in R&D activities in their own industries (see, e.g., Li 2001). This is the reason for every quality leader to be one step ahead.

firm i undertakes R&D at intensity $h_i(j)$ for an infinitesimal time interval dt, then it will succeed in taking the next step up the quality ladder for the targeted product j with probability $h_i(j)dt$. This implies that the number of realized innovations $m(j)$ in each industry j follows a Poisson process with the arrival rate $h(j) = \sum_i h_i(j)$. The industry-specific innovation rate

$$h(j) = \frac{L_h(j)H}{\mu\phi(j)} \tag{2.16}$$

is assumed to depend proportionally on the amount of human capital $L_h(j)H$ devoted to R&D activities in industry j. The inverse of the parameter μ relates the productivity of human capital in R&D relative to its (normalized) productivity in production and is assumed to be equal across industries. The term $\phi(j)$ reflects a negative externality of the number of industry specific innovations in the past by indicating that the realization of further innovations becomes progressively more difficult as the quality level increases. This effect provides a disincentive for challengers to engage in R&D activities in the most progressiv industries which exactly compensates for the higher-profit incentive discussed above.

The Stock Market

The expected discounted profits of a challenger firm winning a patent race in industry j is the stock market value $V_{m(j)+1}(j)$. To participate in an innovation race, firms have to employ human capital in their research labs. According to (2.16), a challenger i who devotes $L_{h,i}(j)H$ units of human capital to R&D at a cost of $L_{h,i}(j)H$ for an infinitesimal time interval dt attains the stock-market value $V_{m(j)+1}(j)$ with probability $[L_{h,i}(j)H/(\mu\phi(j))]dt$. He can finance R&D activities by issuing equity claims which yield nothing in case that the research effort fails but entitle the claimants to the flow of dividends $\pi_{m(j)+1}(j)$ if the effort succeeds.[7] Omitting the uninteresting case where firms undertake no R&D at all, free entry into each innovation race implies $V_{m(j)+1}(j) = \tilde{\lambda}V(j) = \mu\phi(j)$ such that[8]

$$V(j) = \mu\phi(j)/\tilde{\lambda}\,. \tag{2.17}$$

[7]The impact of a cash-in-advance constraint on R&D investment is analyzed in Chu and Cozzi (2014).

[8]We omit the current quality-level index $m(j)$ for brevity.

Since the quality level $\phi(j)$ is constant during every race and only jumping up to $\tilde{\lambda}\phi(j)$ whenever an innovation occurs, it follows that the firm value $V(j)$ is also constant during every innovation race. Every time the quality level increases, however, R&D in the respective industry becomes more difficult implying that the reward for innovating must correspondingly increase to induce further R&D activities of challengers in this industry.

Since there is a continuum of industries and the returns from engaging in innovation races are independently distributed across firms and industries, each household investor minimizes risk by holding a diversified portfolio of stocks. Absence of arbitrage opportunities implies that the expected return on equities of innovators must equal the return on an equal size investment in a riskless bond, i.e.,

$$\pi(j)/V(j) - h(j) = r \;, \tag{2.18}$$

where the expected rate of return on equities of innovators consists of the dividend rates and the risk of losing the dividends due to another firm's quality innovation in the future.

By substituting (2.11), (2.15) and (2.17) into (2.18) we obtain the no-arbitrage condition

$$h(j) + \kappa - \delta = (1-\alpha)\tilde{\lambda} IL/(\mu\Phi) \;,$$

from which we conclude that innovation rates are equal across industries, i.e., $h(j) = h \;\; \forall \;\; j$.

Industrial Dynamics and Quality Growth

The average quality of the top-of-the-line consumer products is $\Phi = \int_0^1 \phi(j)\; dj$. Due to (2.13) the quality of product j jumps up from $\phi(j)$ to $\tilde{\lambda}\phi(j)$ whenever an innovation occurs. Since the innovation rate h is equal across industries, the time derivative of the average quality index is

$$\dot{\Phi} = \int_0^1 (\tilde{\lambda}-1)\phi(j)h\; dj = (\tilde{\lambda}-1)h\Phi \;,$$

such that its growth rate

$$\dot{\Phi}/\Phi = (\tilde{\lambda}-1)h \tag{2.19}$$

depends proportionally on the innovation rate.

The Labor Market

The labor market is perfectly competitive. The share $(1-\theta)$ of workers' human capital is devoted to education. The remaining amount of human capital is employed either in production or in R&D. It follows from (2.14) that the aggregate demand for human capital in the production sector is

$$L_q H = \int_0^1 Q(j) dj = \alpha IL \ ,$$

and from (2.16) that the aggregate demand in the research sector amounts to

$$L_h H = \int_0^1 \mu h \phi(j) \ dj = \mu h \Phi \ .$$

Thus, full employment of workers implies

$$LH = (1-\theta)LH + \alpha IL + \mu h \Phi \ . \tag{2.20}$$

This labor-market clearing condition will be used to analyze the balanced-growth equilibrium for a given level of scientific knowledge and to study growth cycles in response to fundamental scientific discoveries.

The Balanced-Growth Equilibrium

First, we solve the model for a balanced-growth path as an equilibrium path in which all endogenous aggregate variables grow at a constant rate over time. We conclude from (2.6), (2.12) and (2.20) that

$$\dot{H}/H = \kappa(1-\theta) - \delta = \dot{I}/I = \kappa - \delta - \rho \ ,$$

implying a constant share of human capital

$$1-\theta = 1-\rho/\kappa \tag{2.21}$$

devoted to education. It depends positively on the effectiveness of the educational system but negatively on the discount rate. This is the basic growth mechanism as has been emphasized by Lucas (1988). We further conclude from (2.12), (2.19) and (2.20) that

$$\dot{\Phi}/\Phi = (\tilde{\lambda} - 1)h = \dot{I}/I = \kappa - \delta - \rho \ .$$

The steady-state innovation rate is therefore determined as

$$h^* = (\kappa - \delta - \rho)/(\tilde{\lambda} - 1) \ . \tag{2.22}$$

In contrast to predecessor models of R&D-based economic growth, the steady-state innovation rate neither depends on the exogenous labor force as in the scale-variant growth models of Grossman and Helpman (1991a), Aghion and Howitt (1992), and Stokey (1995) nor on the population growth rate as in the semi-endogenous growth model of Segerstrom (1998). Instead, economic growth is endogenously explained in terms of educational and technological parameters. Education and innovation are closely related to each other. The realization of innovations becomes progressively more difficult as technology evolves, but researchers compensate for this deterioration of technological opportunities by continuously improving their skills. Education and innovation appear as in-line engines of economic growth.

Given (2.19) and (2.22), the consumption index (2.4) reads

$$C = \alpha \Phi^{(1-\alpha)/\alpha} I$$

and grows at the scale-invariant rate

$$\dot{C}/C = (1/\alpha)(\kappa - \delta - \rho) \ ,$$

which can be decomposed into quantity growth at rate $\kappa - \delta - \rho$ and quality growth at rate $(1/\alpha - 1)(\kappa - \delta - \rho)$.

Proposition 1: *The long-run innovation rate of the economy depends positively on the effectiveness of education and human-capital accumulation but negatively on the innovation size and the depreciation and discount rates. Education and innovation are the two in-line engines of scale-invariant economic growth.*

Whereas the technological development in any particular industry evolves stochastically, the economy at the aggregate level experiences smooth and non-random processes of human-capital accumulation, innovation and growth.

Scientific Discoveries, Innovation Clusters and Growth Cycles

We now consider a certain point in time where technological opportunities improve, triggered for example by a fundamental scientific discovery. Stadler (2013) has extended the framework of the presented model by adding a Poisson jump process to the movement equation (2.6) of human capital. To illustrate the consequences of such a jump, let us instead consider a single downward jump of parameter μ, reflecting an upward shift of R&D productivity.[9]

Since neither human capital LH nor the quality index Φ can increase discontinuously, it is obvious from (2.20) that the innovation rates h jump up such that aggregate labor demand in the R&D sector remains constant. A cluster of innovations across industries occurs since the pace of technological progress in all industries accelerates. In response to the higher innovation rates, the quality index Φ grows at a higher rate. It follows from the labor-market clearing condition (2.20) that the sum of growth rates of h and Φ must equal the growth rate of H, implying that

$$\dot{h}/h + (\tilde{\lambda} - 1)h = \kappa - \delta - \rho \; .$$

Substituting the steady-state innovation rate h^* from (2.22) leads to the non-linear first-order differential equation

$$\dot{h}/h = -\,(\tilde{\lambda} - 1)(h - h^*) \quad < \quad 0 \; ,$$

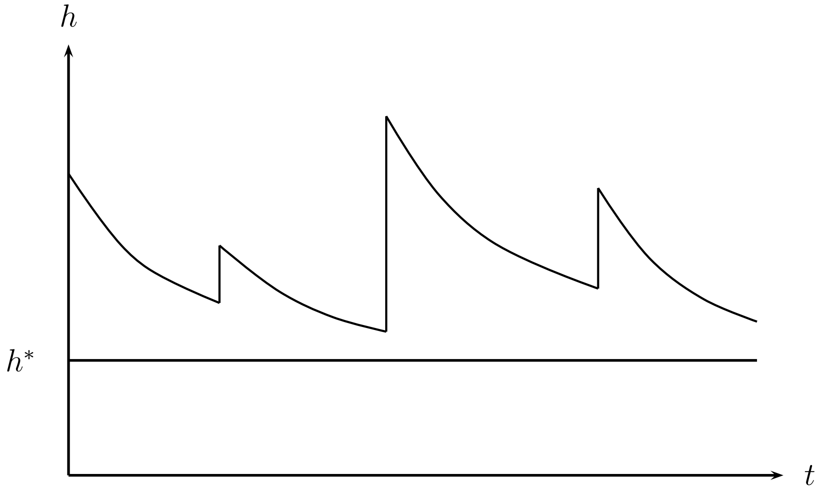
which describes a declining adjustment path of the innovation rate h which converges to the steady-state value h^* when time approaches infinity and no further scientific discovery appears. However, as soon as a further scientific discovery occurs, the innovation rates jump up again and, hence, initialize a new growth cycle, as is illustrated in Figure 1.

Proposition 2: *Scientific discoveries lead to a temporary increase in the innovation and growth rates of the economy, thereby inducing innovation clusters across industries and generating growth cycles.*

If patent protection is imperfect, rival firms are able to imitate the top-of-the-line products. In case of Bertrand competition, entry of imitating firms reduces the flow

[9] A similar mechanism forms the basis for models on general-purpose technologies (see, e.g., Bresnahan and Trajtenberg 1995, Helpman and Trajtenberg 1998, Bresnahan 2010, and Carlaw and Lipsey 2006, 2011).

Figure 1: Innovation Clusters and Growth Cycles



of profits for all incumbent firms to zero. Therefore, under the assumptions holding so far, there is no incentive for firms to engage in imitative activities. However, under more general assumptions it may be profitable for firms to imitate. At least three extensions in this direction are discussed in the literature. First, if the discount factor is sufficiently high, a subgame perfect equilibrium may exist where quality leaders collude and share monopoly profits (see, e.g., Segerstrom 1991, Houser 1998 and Cheng and Tao 1999). Second, imitation of the state-of-the-art technology may be a necessary precondition for firms to participate in the next innovation race (see, e.g., Mukoyama 2003). Third, imitation may be profitable if the copying firm is able to produce at a lower unit cost. This is obviously the case if the imitating firm is located in another country or region which is characterized by a lower wage rate. The next step is therefore to open the economy and to analyze international product cycles characterized by sequences of innovation and imitation.

3 Innovation, Imitation and International Product Cycles

The observation that innovative goods are manufactured in a developed country (the North) until production is relocated to a less developed country (the South), has been the basis for Vernon's (1966) product-cycle theory of international trade. As he claimed, innovative goods are developed and produced in the North until the underlying production technologies are standardized. At this point in time, the production of goods shifts to the less developed South where the wage rate is lower. A product's life comes to its end and a new cycle begins when the product is replaced by a higher-quality one, again developed in the North.

Krugman (1979) has been the first to formalize North-South trade in this spirit, albeit with an exogenous rate of innovation in the North and an exogenous rate of technology transfer to the South. Therefore, his model is concerned with the effects of innovation and imitation, but not with their causes. Models with endogenous innovation by profit-maximizing firms in the North have been presented by Segerstrom, Anant and Dinopoulos (1990), Helpman (1993), and Lai (1998). However, since technology transfer is assumed to be costless in these models, they cannot account for endogenous imitation by profit-maximizing firms in the South.

Grossman and Helpman (1991c) have developed a model of interrelated innovation and imitation processes by profit-maximizing firms in the North and the South which, however, cannot capture a sequence of product cycles in a particular industry since innovative activities are directed to variety expansion via the creation of new industries. In a complementary article, Grossman and Helpman (1991d) have presented a complementary model with quality improvements instead of variety expansion. This seminal model generates stochastic North-South product cycles as the result of a continuing process of innovation and imitation within each single industry. Both versions of the Grossman and Helpman North-South trade model belong to the R&D-based growth models of the first generation.

Dinopoulos and Segerstrom (2007) have extended the Grossman and Helpman (1991c) model of North-South product cycles to a semi-endogenous growth model of the second generation. In their model, the single driving force for innovation and growth is a positive rate of world-population growth which is not only assumed to be time-invariant, but also exogenously given and identical in the North and the South. The increasing labor force goes along with an increasing difficulty of realizing innovations such that the model generates a constant steady-state innovation rate. However, this scenario is rather unrealistic. In fact, population growth rates in the Northern and Southern countries differ to a large extent and decline over time, taking zero or even negative values in some Northern countries. The balanced population-growth property is also theoretically fragile. It can be shown that without population growth, the Dinopoulos and Segerstrom (2007) model generates a stationary equilibrium without innovation, imitation and economic growth.

To avoid this shortcoming, which is common to all semi-endogenous growth models, Stadler (2007) has extended the Dinopoulos and Segerstrom (2007) approach by considering the skill acquisition of workers in order to replace exogenous population growth by endogenous human-capital accumulation. This modification prevents the global economy from reaching a steady state without technological dynamics when the population growth goes down to zero. In the following, we present that extended version of the Dinopoulos and Segerstrom (2007) North-South trade model to study the industrial dynamics and aggregate growth in a global economy.

The Product Markets

We consider a world economy consisting of two countries or regions, the North and the South, indexed by $\iota \in \{N, S\}$. The North consists of the developed countries, whereas the South consists of those developing countries which have already joined the world trading system and participate in free trade without restriction.

The global economy is populated by a fixed measure of households in the North, L^N, and in the South, L^S. Human capital per capita is H^N in the North and H^S in the South, such that $(L^N H^N + L^S H^S)$ is the global supply of human capital. As already stated in Section 2, households share identical preferences and maximize their discounted utility (2.1), subject to their budget constraints, such that

$$q^\iota(j) = \frac{\phi(j) p(j)^{-\frac{1}{1-\alpha}} I^\iota}{\int_0^1 \phi(j) p(j)^{-\frac{\alpha}{1-\alpha}}\, dj} \ , \quad \iota = N, S \ . \tag{3.1}$$

The production technologies in both regions coincide. However, each firm in the North has a constant unit cost equal to w^N and each firm in the South has a constant unit cost equal to w^S. We normalize the wage rate in the South, such that the relative wage $\omega = w^N / w^S$ is constant on a balanced growth path.

As in Section 2, we restrict our analysis to the case of drastic innovations, i.e., $1/\alpha < \lambda$. This implies that all Northern quality leaders charge the unconstrained monopoly price $p^N(j) = p^N = (1/\alpha) w^N$.[10] Hence, we derive from (3.1) each Northern

[10]The condition $(1/\alpha) w^N < \lambda w^S$ is sufficient to generate this price-setting behavior.

firm's demand function

$$Q^N(j) = \phi(j)(p^N)^{-\frac{1}{1-\alpha}} P_C^{\frac{\alpha}{1-\alpha}} (I^N L^N + I^S L^S) \; , \tag{3.2}$$

where P_C is the quality-adjusted price index as defined in (2.4), and the flow of profits

$$\pi^N(j) = (1/\alpha - 1) w^N \phi(j)(p^N)^{-\frac{1}{1-\alpha}} P_C^{\frac{\alpha}{1-\alpha}} (I^N L^N + I^S L^S) \tag{3.3}$$

from selling to Northern and Southern consumers.

A Southern firm that succeeds in imitating the quality of a top-of-the-line product manufactured by a Northern firm gains a cost advantage over the Northern competitor if $w^N > w^S$, which will be assumed to hold in the steady-state equilibrium. The copying firm is assumed to undercut the price of the previous Northern producer by setting the unconstrained monopoly price $p^S(j) = p^S = (1/\alpha)w^S$.[11] From (3.1) we derive each Southern firm's demand function

$$Q^S(j) = \phi(j)(p^S)^{-\frac{1}{1-\alpha}} P_C^{\frac{\alpha}{1-\alpha}} (I^N L^N + I^S L^S) \tag{3.4}$$

and the flow of profits

$$\pi^S(j) = (1/\alpha - 1) w^S \phi(j)(p^S)^{-\frac{1}{1-\alpha}} P_C^{\frac{\alpha}{1-\alpha}} (I^N L^N + I^S L^S) \; . \tag{3.5}$$

We now turn to the dynamics of technological progress in the North and the transfer of the improved technologies to the South.

Dynamics of Innovation and Imitation

R&D competition takes the form of stochastic innovation races between Northern firms. The number of innovations realized in each industry j follows a Poisson process with the arrival rate $h(j) = \sum_i h_i(j)$ which is specified according to (2.16) as

$$h(j) = \frac{L_h^N(j) H^N}{\mu \phi(j)} \; . \tag{3.6}$$

Firms in the South are assumed to undertake only imitative research targeted at imitating the quality of the top-of-the-line products which are actually produced

[11]The condition $(1/\alpha)w^S < w^N$ is sufficient to generate this price-setting behavior.

in the North. Corresponding to the innovation races, this kind of competition is assumed to take the form of stochastic imitation races between Southern firms. Each Southern firm i may target its imitative activities at any of the state-of-the-art products currently manufactured in the North. If it undertakes imitative activities at intensity $k_i(j)$ for an infinitesimal time interval dt, it will succeed in copying the targeted product j with probability $k_i(j)dt$. This implies that the number of imitations realized in each industry j follows a Poisson process with the arrival rate $k(j) = \sum_i k_i(j)$, given by

$$k(j) = \frac{L_k^S(j)H^S}{\nu\phi(j)} \ , \tag{3.7}$$

where ν is a measure of the technological difficulty in realizing an imitation and is closely related to the strength of protection of intellectual property rights. The arrival rate of imitations is assumed to depend proportionally on the amount of human capital $L_k^S(j)H^S$ devoted to imitative activities. The presence of the term $\phi(j)$ again reflects a negative externality of the technology level reached in industry j in the past.

The Global Stock Market

The expected discounted flow of profits of a Northern challenger winning an innovation race is the stock market value $V^N_{m(j)+1}(j)$. To participate in an innovation race, Northern firms have to employ workers' human capital in their research labs. As derived in (2.17), free entry into each innovation race implies

$$V^N(j) = \mu w^N \phi(j)/\tilde{\lambda} \ . \tag{3.8}$$

The firm value $V^N(j)$ is constant during an innovation race until the next innovation of a Northern firm or an imitation of a Southern firm occurs. This leads to the no-arbitrage condition

$$\pi^N(j)/V^N(j) - h(j) - k(j) = r \ . \tag{3.9}$$

By substituting (2.11), (3.3) and (3.8) into (3.9) we obtain

$$h(j) + k(j) + \kappa - \delta = (1/\alpha - 1)\mu^{-1}\tilde{\lambda}(p^N)^{-\frac{1}{1-\alpha}} P_C^{\frac{\alpha}{1-\alpha}} (I^N L^N + I^S L^S) \ . \tag{3.10}$$

In the South, free entry into each imitation race implies

$$V^S(j) = \nu w^S \phi(j) \tag{3.11}$$

and the no-arbitrage condition reads

$$\pi^S(j)/V^S(j) - h(j) \ = \ r \, . \tag{3.12}$$

The product manufactured by a Southern incumbent will not be imitated by another Southern firm since there is no reward for copying already copied products under Bertrand competition. By substituting (2.11), (3.5), and (3.11) into (3.12) we obtain

$$h(j) + \kappa - \delta = (1/\alpha - 1)\nu^{-1}(p^S)^{-\frac{1}{1-\alpha}} P_C^{\frac{\alpha}{1-\alpha}} (I^N L^N + I^S L^S) \, . \tag{3.13}$$

It can be concluded successively from (3.13) and (3.10) that both, innovation and imitation rates, are equal across industries, i.e., $h(j) = h$ and $k(j) = k \; \forall \; j$.

To solve for the relative product price in the North, we divide (3.13) by (3.10) to obtain

$$\frac{p^N}{p^S} = \frac{w^N}{w^S} = \omega = \left(\frac{\nu \tilde{\lambda}(h + \kappa - \delta)}{\mu(h + k + \kappa - \delta)} \right)^{1-\alpha} \, , \tag{3.14}$$

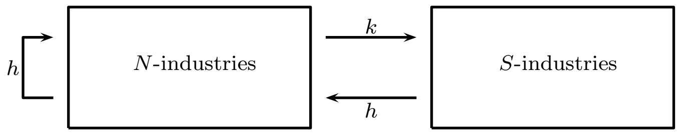
which is increasing in the rate of innovation but decreasing in the rate of imitation. As noted in footnote 11 above, we have to assume that $\omega > 1/\alpha$.

Industrial Dynamics and Quality Growth

At each point in time, a share n^N of industries, called "N-industries" have Northern incumbents and a share n^S of industries, called "S-industries" have Southern incumbents whereby $n^N + n^S = 1$. Northern firms undertake innovative activities in all industries while Southern firms undertake imitative activities only in the N-industries where production is currently in the North. Due to Bertrand competition, imitations in the S-industries would not be profitable. However, if a Southern firm is successful in imitating the product of a Northern quality leader, production shifts to the South because the unit cost of production is lower there. As soon as a Northern firm is successful in a quality innovation of a product which is currently manufactured in the South, production shifts back to the North. As is illustrated in Figure

2, each product switches randomly across the two types of industries with transition probabilities depending on the Poisson arrival rates associated with innovative and imitative activities.

Figure 2: Innovation, Imitation and Industrial Dynamics



Since n^N is constant over time in a steady-state equilibrium, the flow into the N-industries must equal the flow out of the N-industries, i.e. $n^S h = n^N k$, such that

$$n^N = \frac{h}{h+k}; \quad n^S = \frac{k}{h+k} \; . \tag{3.15}$$

The share of industries with Northern incumbents is an increasing function of the rate of innovation and a decreasing function of the rate of imitation. The opposite holds for the share of industries with Southern incumbents.

The average quality of all products can be decomposed to $\Phi = \Phi^N + \Phi^S$, where

$$\Phi^N \equiv \int_{n^N} \phi(j)dj = \int_{n^N} \tilde{\lambda}^{m(j)} dj$$

is the aggregate quality of the Northern products and

$$\Phi^S = \int_{n^S} \phi(j)dj = \int_{n^S} \tilde{\lambda}^{m(j)} dj$$

is the aggregate quality of the Southern products. The time derivative of Φ^N is

$$\begin{aligned} \dot{\Phi}^N &= \int_{n^N} (\tilde{\lambda}^{m(j)+1} - \tilde{\lambda}^{m(j)})\, h\, dj \; + \int_{n^S} \tilde{\lambda}^{m(j)+1}\, h\, dj \; - \int_{n^N} \tilde{\lambda}^{m(j)}\, k\, dj \\ &= (\tilde{\lambda} - 1)h\Phi^N + \tilde{\lambda} h \Phi^S - k\Phi^N \end{aligned}$$

and the time derivative of Φ^S is

$$\dot{\Phi}^S = \int_{n^N} \tilde{\lambda}^{m(j)} k\, dj \; - \int_{n^S} \tilde{\lambda}^{m(j)}\, h\, dj = k\Phi^N - h\Phi^S \; .$$

This implies the growth rates

$$\dot{\Phi}^N/\Phi^N = (\tilde{\lambda} - 1)h + \tilde{\lambda}h\Phi^S/\Phi^N - k$$

and

$$\dot{\Phi}^S/\Phi^S = k\Phi^N/\Phi^S - h \ .$$

Obviously, the growth rates of Φ^N and Φ^S are constant over time only if they are equal. It follows from $\dot{\Phi}^N/\Phi^N = \dot{\Phi}^S/\Phi^S$ that $\Phi^N/\Phi^S = \tilde{\lambda}h/k$ and, by definition,

$$\Phi^N = \frac{\tilde{\lambda}h}{\tilde{\lambda}h + k}\,\Phi \ ; \quad \Phi^S = \frac{k}{\tilde{\lambda}h + k}\,\Phi \ , \tag{3.16}$$

Using (3.15), this implies

$$\frac{\Phi^N}{n^N} = \frac{\tilde{\lambda}(h+k)}{\tilde{\lambda}h + k}\,\Phi \quad > \quad \frac{\Phi^S}{n^S} = \frac{h+k}{\tilde{\lambda}h + k}\,\Phi \ ,$$

indicating that the average quality of products manufactured in the North is generally higher than the average quality of products manufactured in the South.

The Labor Markets

It is assumed that workers can move freely across firms and sectors within each region but not across the regions. According to (2.21), in both regions a constant share $1 - \rho/\kappa$ of human capital is devoted to education. The remaining amount of human capital is devoted to production and to R&D. It follows from (3.2) that the aggregate demand for human capital in the Northern production sector is

$$\int_{n^N} L_q^N(j)H^N dj = \int_{n^N} Q^N(j)dj = \Phi^N(p^N)^{-\frac{1}{1-\alpha}} P_C^{\frac{\alpha}{1-\alpha}}(I^N L^N + I^S L^S)$$

and from (3.6) that the aggregate demand for human capital in the Northern research sector amounts to

$$\int_0^1 L_h^N(j)H^N dj = \int_0^1 \mu h\phi(j)dj = \mu h\Phi \ .$$

Thus, full employment of Northern workers implies that

$$L^N H^N = (1 - \rho/\kappa)L^N H^N + \Phi^N(p^N)^{-\frac{1}{1-\alpha}} P_C^{\frac{\alpha}{1-\alpha}}(I^N L^N + I^S L^S) + \mu h\Phi \ . \tag{3.17}$$

Similar calculations apply for the Southern labor market. It follows from (3.4) that the aggregate demand for human capital in the Southern production sector is

$$\int_{n^S} L_q^S(j)H^S dj = \int_{n^S} Q^S(j)dj = \Phi^S(p^S)^{-\frac{1}{1-\alpha}} P_C^{\frac{\alpha}{1-\alpha}}(I^N L^N + I^S L^S) \ ,$$

and from (3.7) that the aggregate demand for human capital in the Southern research sector is

$$\int_{n^N} L_k^S(j)H^S dj = \int_{n^N} \nu k \phi(j)dj = \nu k \Phi^N \ .$$

Thus, full employment of Southern workers implies that

$$L^S H^S = (1-\rho/\kappa)L^S H^S + \Phi^S(p^S)^{-\frac{1}{1-\alpha}} P_C^{\frac{\alpha}{1-\alpha}}(I^N L^N + I^S L^S) + \ \nu k \Phi^N \ . \tag{3.18}$$

The equation system (3.11), (3.14), (3.16), (3.17), and (3.18) is sufficient to solve the model for a steady-state equilibrium.

The Balanced-Growth Equilibrium

In the balanced-growth equilibrium, the growth rates are determined by

$$\dot{I}^\iota/I^\iota = \dot{H}^\iota/H^\iota = (\kappa-\delta-\rho) = \dot{\Phi}^\iota/\Phi^\iota = \dot{\Phi}/\Phi = (\tilde{\lambda}-1)h \ ; \quad \iota = N, S \ ,$$

such that the innovation rate is again

$$h^* = \frac{\kappa-\delta-\rho}{\tilde{\lambda}-1} \ .$$

The steady-state innovation rate of the open economy coincides with the one derived in (2.22) for the closed economy. To derive the explanatory factors of the imitation rate k, we substitute (3.10) and (3.16) into (3.17) to obtain the Northern steady-state condition

$$\rho/\kappa = \mu \frac{\Phi}{L^N H^N}\left[\frac{\alpha}{1-\alpha}\frac{(h+k+\kappa-\delta)h}{\tilde{\lambda}h+k} + h\right] \ , \tag{3.19}$$

and substitute (3.13) and (3.16) into (3.18) to obtain the Southern steady-state condition

$$\rho/\kappa = \nu \frac{\Phi}{L^S H^S}\left[\frac{\alpha}{1-\alpha}\frac{(h+\kappa-\delta)k}{\tilde{\lambda}h+k} + \frac{\tilde{\lambda}hk}{\tilde{\lambda}h+k}\right] \ . \tag{3.20}$$

In the balanced-growth equilibrium, the innovation and imitation rates, and the ratios Φ/H^N and Φ/H^S are constant over time.

The products in each industry follow stochastic life cycles with rather different histories. A particular product might be manufactured in the North for a while before a Southern firm succeeds in imitating the technology. Then production shifts to the South where the product is manufactured until being upgraded again in the North. Alternatively, the product might be improved several times in succession by various Northern firms before it is imitated by a Southern firm. An appropriate measure of the average length of a North-South product cycle is $(1/k + 1/h)$. The first term indicates how long, on average, a product will be produced in the North before being imitated by a Southern firm. Analogously, the second term indicates how long, on average, a product will be manufactured by that Southern firm before being upgraded again by a Northern innovator.

Globalization and Intellectual Property Rights

The steady-state equilibrium of the model enables us to derive some comparative-static effects of globalization on the dynamics of innovation and imitation. Globalization is modeled as an expansion in the size of the South. Even if less developed, each country joining the world trading system will increase the labor force L^S. To keep the analysis tractable, we assume that the per-capita human capital of the joining country equals that of the already integrated countries in the South. In order to concentrate on a steady-state equilibrium, we further have to assume that the effectiveness of education, measured by education parameter κ, is equal in the North and the South.[12] However, the influence of different human-capital growth rates can be captured within the model by a sequence of jumps in the relative stock of human capital H^S/H^N.

To derive the comparative-static effects, we totally differentiate the equation system

[12]A smaller effectiveness parameter in the South would induce developing countries to continuously fall behind the developed counties. A higher effectiveness parameter in the South would induce developing countries to continuously catch up which would contradict the assumption of only Northern firms being able to innovate. Of course, both alternative assumptions are not compatible with a balanced steady-state growth equilibrium of the global economy.

(3.19) and (3.20). Making use of

$$\frac{\partial}{\partial k}\left(\frac{h+k+\kappa-\delta}{\tilde{\lambda}h+k}\right)=-\frac{\rho}{(\tilde{\lambda}h+k)^2}\;<\;0$$

and

$$\frac{\partial}{\partial k}\left(\frac{k}{\tilde{\lambda}h+k}\right)=\frac{\tilde{\lambda}h}{(\tilde{\lambda}h+k)^2}\;>\;0$$

we obtain $dk/dL^S > 0$ and $dk/d\nu < 0$. An increase in the size of the South L^S leads to an increase in the innovation rate. It follows from (3.19) that this in turn increases the ratio Φ^N/H^N and thus implies a short-run increase in the innovation rate. The long-run innovation rate h^*, however, is not affected by dL^S.

Proposition 3: *Globalization measured by an increase in the size of the South leads to a temporary increase in the innovation rate and to a permanent increase in the imitation rate so that the average length of a North-South product cycle decreases.*

The intuition behind this result is obvious. More demand in the South increases the rate of imitating the top-of-the-line products currently manufactured by Northern firms. This higher rate of technology transfer implies that production is relocated from the high-wage North to the low-wage South such that Northern workers are set free for employment in R&D. As can be seen from (3.14), the Northern relative wage rate falls and gives Northern firms an incentive to raise their innovative activities. The innovation rates jump up and accelerate technological progress, but workers are partially shifted back into production as innovation becomes more difficult as the quality level increases. In the long run, globalization increases the fraction of Northern human capital devoted to R&D whereas the innovation rate remains constant.

Nowadays, the question of the strength of protection of intellectual property rights has become an important topic in the theory of international trade. We capture a stronger protection of intellectual property rights by an increase in the parameter ν measuring the difficulty of imitation. The comparative statics correspond to those of a variation of L^S.

Proposition 4: *Stronger protection of intellectual property rights measured by an increase in the difficulty for Southern firms to realize imitations leads to a temporary decrease in the innovation rate and to a permanent decrease in the imitation rate so that the average length of a North-South product cycle increases.*

Of course, stronger protection of intellectual property rights induces Southern firms to devote less human capital to imitative activities. The lower rate of imitation increases the demand for Northern workers. The Northern relative wage rate increases until the additional employment of human capital in production is offset by an equal decrease in the demand for human capital in the Northern R&D labs. The innovation rate temporarily declines. In the long run, however, the innovation rate remains constant, even if a smaller fraction of Northern human capital is devoted to R&D.

Imitation is an important channel through which for the technology transfer from developed countries to developing countries. However, as examined, e.g., by Branstetter et al. (2006), international technology transfer occurs not only across rival firms via imitation, but also within multinational firms via foreign direct investment. Such a complementary model of technology transfer by multinational firms is presented in the next section.

4 Innovation and Technology Transfer via Foreign Direct Investment

North-South trade models with technology transfer within multinational firms include Glass and Saggi (2002), Sener (2006), and Glass and Wu (2006). In these models, however, a stronger protection of intellectual property rights leads to a lower rate of technology transfer from North to South. The empirically observed increase in the rate of technology transfer that results from stronger protection is consistent with the implications of the North-South trade models developed by Helpman (1993), Lai (1998), and Branstetter et al. (2007). However, these papers assume that international technology adaption within multinational firms is costless and thus cannot account for the observed increase in R&D spending by foreign affiliates of multinationals. Several empirical studies have documented that research activities conducted by affiliates in developing countries is focused on the absorption of parent-firm technology (see, e.g., Kuemmerle 1999).

Recently, Dinopoulos and Segerstrom (2010) have developed a North-South trade model that is consistent with the above-mentioned empirical evidence. As the predecessor model of Dinopoulos and Segerstrom (2007), this model is a semi-endogenous

R&D-based growth model. In order to develop a fully endogenous Schumpeterian growth model of the third generation, we adopt the idea from Dinopoulos and Segerstrom (2010) but again replace the assumption of exogenous population growth by endogenous human-capital accumulation. This extension allows us to present a model of multinational firms in line with the models presented in the former sections.

As before, we consider a global economy consisting of two countries or regions: a high-wage North and a low-wage South. Human capital is the only factor of production and grows at an endogenous rate in both regions. It is employed in four distinct activities: education, manufacturing of consumption goods, innovative research activities and adaptive research activities. Innovations are realized by firms in the North, adoptions are realized by firms in the South. There is free trade between the two regions.

In this global economy, Northern firms hire workers to engage in R&D with the aim of developing higher-quality products. A successful firm becomes a Northern quality leader and earns global monopoly profits from producing and selling the state-of-the art quality product in its industry. As an additional feature, compared to Section 3, a Northern quality leader can hire Southern workers to engage in adaptive research with the aim of transferring this technology to the low-wage South. When successful, a firm establishes a foreign affiliate and earns even higher global monopoly profits because of lower wages in the South. A fraction of profits is repatriated back to the Northern stockholders. Adaptive research can be interpreted as foreign direct investment because it represents the cost that Northern quality leaders have to incur in order to transfer their technology to foreign affiliates. Further, Northern quality leaders control the intensity of adaptive research such that their global profits are maximized.

The Product Markets

Each Northern quality leader faces constant unit cost of production equal to the Northern wage rate w^N. Likewise, each foreign affiliate in the South has constant unit cost equal to the Southern wage rate w^S. We solve the model for a steady-state equilibrium where the North has a higher wage rate than the South such that production shifts from North to South as soon as a Northern leader is successful in adaptive research. In addition, we assume that the quality improvement is sufficiently large for a Northern quality leader to produce at lower quality-adjusted unit costs than a foreign affiliate producing a product with a quality one step below. As a result, Northern quality leaders can drive foreign affiliates producing lower quality products out of business even though the latter have a wage-based cost advantage.

Both, the Northern quality leaders N as well as the Southern affiliates F maximize the flow of global profits by setting the unconstrained monopoly prices, $p^N = (1/\alpha)w^N$ and $p^F = (1/\alpha)w^S$.

Each foreign affiliate, but not the Northern leaders, faces an exogenously given risk that its technology becomes imitated. At each point in time, there is an instantaneous probability k that a foreign affiliate's product is imitated by a competitive fringe of Southern firms S. All imitated products are produced in the South and offered at the Bertrand price $p^S = w^S$.

This leads to firms' demand functions

$$Q^\iota(j) = \phi(j)\ (p^\iota)^{-\frac{1}{1-\alpha}}\ P_C^{\frac{\alpha}{1-\alpha}}(I^N L^N + I^S L^S)\ , \quad \iota = N, F, S \tag{4.1}$$

and the profits

$$\pi^N(j) = (1/\alpha - 1)\ w^N\ \phi(j)\ (p^N)^{-\frac{1}{1-\alpha}}\ P_C^{\frac{\alpha}{1-\alpha}}(I^N L^N + I^S L^S) \tag{4.2}$$

and

$$\pi^F(j) = (1/\alpha - 1)\ w^S\ \phi(j)\ (p^F)^{-\frac{1}{1-\alpha}}\ P_C^{\frac{\alpha}{1-\alpha}}(I^N L^N + I^S L^S)\ . \tag{4.3}$$

Due to Bertrand competition, the imitating firms in the South realize no profits such that $\pi^S(j) = 0$.

Dynamics of Innovation, Adaption and Imitation

Innovation dynamics are captured analogously to Sections 2 and 3. If Northern challenger firms employ $L_h^N(j)H^N$ units of human capital in innovative research, they are successful in developing the next higher-quality product in industry j with instantaneous probability

$$h(j) = \frac{L_h^N(j)H^N}{\mu\phi(j)}\ . \tag{4.4}$$

The returns to R&D activities are independently distributed across firms, industries and over time. If the foreign affiliate of a Northern quality leader employs $L_\ell^S(j)H^S$ units of human capital in adaptive research, then the Northern firm is successful in shifting its production to the South with instantaneous probability

$$\ell(j) = \frac{L_\ell^S(j)H^S}{\eta\phi(j)} , \tag{4.5}$$

where η measures the difficulty of technology adaption. A Northern quality leader is more likely to be successful in transferring its production to the South when it employs more human capital.

The Global Stock Market

Free entry into each innovation race implies that the expected benefit from innovative R&D must be equal to the corresponding R&D cost. This implies $V_{m(j)+1}^N(j) = w^N\mu\tilde{\lambda}\phi(j)$ such that

$$V^N(j) = w^N\mu\phi(j)/\tilde{\lambda} . \tag{4.6}$$

Foreign affiliates of Northern quality leaders engage in adaptive research. If successful, the expected discounted profit earned by the firm is $V^F(j) - V^N(j)$, where $V^F(j)$ is the market value of the foreign affiliate after success. When a technology transfer occurs, the foreign affiliate has to pay its Northern parent firm the royalty payment $V^N(j)$ for the use of its technology in the South. Therefore, what matters for adaptive research is the gain in expected discounted profits, $V^F(j) - V^N(j)$. A foreign affiliate engages in adaptive research activities if

$$V^F(j) - V^N(j) = w^S\eta\phi(j) ,$$

such that

$$V^F(j) = (w^N\mu/\tilde{\lambda} + w^S\eta)\phi(j) . \tag{4.7}$$

Consumers finance both types of innovative and adaptive activity through a global stock market. At each point in time there are two types of firms having positive stock-market values, Northern quality leaders producing in the North, and foreign affiliates producing in the South. Since the returns to innovative and adaptive investments are independent across firms, consumers can completely diversify the idiosyncratic risk by holding a diversified portfolio of stocks. At each point in time, the rate of return from holding any of the stocks must be the same as the rate of return r from holding a risk-free bond. The no-arbitrage condition for holding a stock issued by an incumbent Northern quality leader is

$$\pi^N(j)/V^N(j) - h(j) = r \; . \tag{4.8}$$

Substituting (2.11), (4.2) and (4.6) into (4.8) gives

$$h(j) + \kappa - \delta = (1/\alpha - 1)\mu^{-1}\tilde{\lambda}(p^N)^{-\frac{1}{1-\alpha}} P_C^{\frac{\alpha}{1-\alpha}} (I^N L^N + I^S L^S) \tag{4.9}$$

such that innovation rates are equal across markets, $h(j) = h$. The no-arbitrage condition for holding a stock issued by a multinational firm that produces in the South is

$$\pi^F(j)/V^F(j) - h - k = r \; . \tag{4.10}$$

Substituting (2.11), (4.3) and (4.7) into (4.10) gives

$$(h + k + \kappa - \delta)(\eta + \omega\mu/\tilde{\lambda}) = (1/\alpha - 1)(p^F)^{-\frac{1}{1-\alpha}} P_C^{\frac{\alpha}{1-\alpha}} (I^N L^N + I^S L^S) \; . \tag{4.11}$$

From (4.9) and (4.11) the relative prices and wages $\omega = w^N/w^S = p^N/p^F$ are determined implicitly by the polynomial

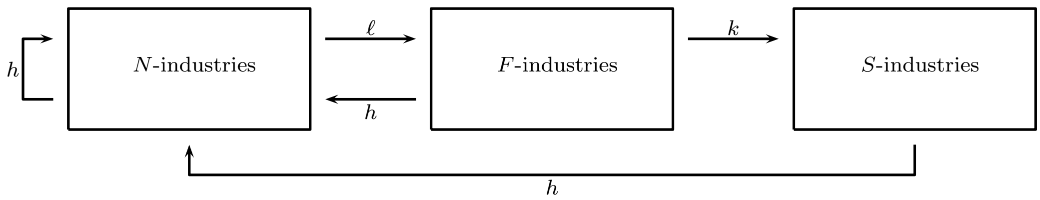
$$[(h + \kappa - \delta)/(h + k + \kappa - \delta)]\omega^{1/(1-\alpha)} - \omega = \eta\tilde{\lambda}/\mu \; , \tag{4.12}$$

The long-run innovation rate is again determined by (2.22). Then the expression on the left hand side of (4.12) is negative at $\omega = 1$, strictly increasing in ω for $\omega > 1$ and approaching infinity for $\omega \to \infty$.

Industrial Dynamics and Quality Growth

At each point in time, there are three types of industries in the global economy: a share n^N of N-industries where products are manufactured by Northern quality leaders, a share n^F of F-industries where products are manufactured in the South by foreign affiliates of multinational firms and a share n^S of S-industries where products are manufactured in the South by competitive-fringe firms. As is illustrated in Figure 3, each product can switch randomly across these three types of industries with transition probabilities that depend on the Poisson arrival rates associated with innovative, adaptive and imitative activities.

Figure 3: Innovation, Adaption, Imitation, and Industrial Dynamics



The shares of industries must be constant in a steady-state equilibrium. This implies that the flow into the N-industries must be equal to flow out of the N-industries, that is $(n^F + n^S)h = n^N\ell$. Additionally, the flow into the S-industries must be equal to the flow out of the S-industries, $n^F k = n^S h$. Together with the requirement that $n^N + n^F + n^S = 1$, these flow equations imply that

$$n^N = \frac{h}{h+\ell}\ ; \quad n^F = \frac{h\ell}{(h+k)(h+\ell)}\ ; \quad n^S = \frac{k\ell}{(h+k)(h+\ell)}\ . \tag{4.13}$$

The average quality of all products can be decomposed into three parts, $\Phi = \Phi^N + \Phi^F + \Phi^S$, where

$$\Phi^N \equiv \int_{n^N} \phi(j)dj = \int_{n^N} \tilde{\lambda}^{m(j)}dj$$

is a measure of product quality for all products manufactured in the North,

$$\Phi^F \equiv \int_{n^F} \phi(j)dj = \int_{n^F} \tilde{\lambda}^{m(j)}dj\ ,$$

is a measure of product quality for products manufactured by foreign affiliates and

$$\Phi^S = \int_{n^S} \phi(j)dj = \int_{n^S} \tilde{\lambda}^{m(j)}dj\ .$$

is a measure of product quality for products manufactured by Southern firms. The time derivative of Φ^N is

$$\dot{\Phi}^N = \int_{n^N} (\tilde{\lambda}^{m(j)+1} - \tilde{\lambda}^{m(j)})\, h\, dj \; + \int_{n^F+n^S} \tilde{\lambda}^{m(j)+1}\, h\, dj \; - \int_{n^N} \tilde{\lambda}^{m(j)}\, \ell\, dj$$
$$= (\tilde{\lambda} - 1)h\Phi^N + \tilde{\lambda}h(\Phi^F + \Phi^S) - \ell\Phi^N \ ,$$

the time derivative of Φ^F is

$$\dot{\Phi}^F = \int_{n^N} \tilde{\lambda}^{m(j)} \ell\, dj \; - \int_{n^F} \tilde{\lambda}^{m(j)}\, h\, dj - \int_{n^F} \tilde{\lambda}^{m(j)}\, k\, dj = \ell\Phi^N - h\Phi^F - k\Phi^F \ ,$$

and the time derivative of Φ^S is

$$\dot{\Phi}^S = \int_{n^F} \tilde{\lambda}^{m(j)} k\, dj \; - \int_{n^S} \tilde{\lambda}^{m(j)}\, h\, dj = k\Phi^F - h\Phi^S \ .$$

This implies the growth rates

$$\dot{\Phi}^N/\Phi^N = (\tilde{\lambda} - 1)h + \tilde{\lambda}h\Phi^S/\Phi^N - k \ ,$$

$$\dot{\Phi}^F/\Phi^F = \ell\Phi^N/\Phi^F - h - k \ ,$$

and

$$\dot{\Phi}^S/\Phi^S = k\Phi^N/\Phi^S - h \ .$$

The growth rates of Φ, Φ^N, Φ^F and Φ^S are constant over time only if $\Phi^N/\Phi^S = \tilde{\lambda}h/k$ and (due to $\Phi = \Phi^N + \Phi^F + \Phi^S$)

$$\Phi^N = \frac{\tilde{\lambda}h}{\tilde{\lambda}h + \ell}\, \Phi \ ; \quad \Phi^F = \frac{\tilde{\lambda}h\ell}{(\tilde{\lambda}h + k)(\tilde{\lambda}h + \ell)}\, \Phi \ ; \quad \Phi^S = \frac{k\ell}{(\tilde{\lambda}h + k)(\tilde{\lambda}h + \ell)}\, \Phi \ . \quad (4.14)$$

Using (4.13), this implies

$$\frac{\Phi^N}{n^N} = \frac{\tilde{\lambda}(h + \ell)}{\tilde{\lambda}h + \ell}\, \Phi \quad > \quad \frac{\Phi^F}{n^F} = \frac{\tilde{\lambda}(h + k)(h + \ell)}{(\tilde{\lambda}h + k)(\tilde{\lambda}h + \ell)}\, \Phi \ > \quad \frac{\Phi^S}{n^S} = \frac{(h + k)(h + \ell)}{(\tilde{\lambda}h + k)(\tilde{\lambda}h + \ell)}\, \Phi \ .$$

Thus, the average quality of products manufactured in the North is higher than the average quality of products manufactured by Southern affiliates which in turn is higher than the average quality of products manufactured by competitive-fringe firms in the South.

The Labor Markets

Full employment of labor prevails at each instant in time and wages adjust to equalize labor demand and supply. Northern labor is employed in three activities: education, production of consumer goods, and innovative research. It follows from (4.1) that the aggregate demand for human capital in the Northern production sector is

$$\int_{n^N} L_q^N(j)H^N dj = \int_{n^N} Q^N(j)dj = \Phi^N (p^N)^{-\frac{1}{1-\alpha}} P_C^{\frac{\alpha}{1-\alpha}} (I^N L^N + I^S L^S) \ .$$

All industries are targeted by Northern firms engaged in innovative activities. It follows from (4.4) that the aggregate demand for human capital in the Northern research sector is

$$\int_0^1 L_h^N(j)H^N dj = \int_0^1 \mu h \phi(j)dj = \mu h \Phi \ .$$

Thus, full employment of Northern workers implies that

$$L^N H^N = (1-\rho/\kappa)L^N H^N + \Phi[\tilde{\lambda}h/(\tilde{\lambda}h+\ell)](p^N)^{-\frac{1}{1-\alpha}} P_C^{\frac{\alpha}{1-\alpha}} (I^N L^N + I^S L^S) + \mu h \Phi \ . \tag{4.15}$$

Human capital of Southern workers can be employed in four activities: education, production by foreign affiliates of multinational firms, adaptive research, and production by Southern firms. It follows from (4.1) that the aggregate demand for human capital in Southern production sector is

$$\int_{n^F} L_q^S(j)H^S dj = \int_{n^F} Q^F(j)dj = \Phi^F (p^F)^{-\frac{1}{1-\alpha}} P_C^{\frac{\alpha}{1-\alpha}} (I^N L^N + I^S L^S)$$

by the foreign affiliates and

$$\int_{n^S} L_q^S(j)H^S dj = \int_{n^S} Q^S(j)dj = \Phi^S (w^S)^{-\frac{1}{1-\alpha}} P_C^{\frac{\alpha}{1-\alpha}} (I^N L^N + I^S L^S)$$

by the competitive-fringe firms. Finally, it follows from (4.5) that the aggregate demand for human capital in adaptive research is

$$\int_{n^N} L_\ell^S H^S dj = \int_{n^N} \eta \ell \phi(j)dj = \eta \ell \Phi^N \ .$$

Thus, full employment of Southern workers implies that

$$L^S H^S = (1-\rho/\kappa)L^S H^S + [\Phi\ell/(\tilde{\lambda}h+\ell)][(p^F)^{-\frac{1}{1-\alpha}} P_C^{\frac{\alpha}{1-\alpha}} (I^N L^N + I^S L^S)\Psi(k) + \ \eta\tilde{\lambda}h] \ , \tag{4.16}$$

where $\Psi(k) \equiv (\tilde{\lambda}h + \xi k)/(\tilde{\lambda}h + k)$; $\xi(k) \equiv (1/\alpha)^{1/(1-\alpha)} > 1$, is increasing in the rate of imitation, i.e. $\Psi'(k) > 0$.

The Balanced-Growth Equilibrium

To derive the factors explaining the technology-adaption rate ℓ, we substitute (4.9) into (4.15) to obtain the Northern steady-state condition

$$\rho/\kappa = \frac{\mu h \Phi}{L^N H^N}\left[\frac{\alpha}{1-\alpha}\frac{h+\kappa-\delta}{\tilde{\lambda}h+\ell} + 1\right] \tag{4.17}$$

and substitute (4.11) into (4.16) to obtain the Southern steady-state condition

$$\rho/\kappa = \frac{\ell\Phi}{(\tilde{\lambda}h+\ell)L^S H^S}\left[\frac{\alpha}{1-\alpha}(\eta + \mu\omega/\tilde{\lambda})(h+k+\kappa-\delta)\Psi(k) + \eta\tilde{\lambda}h\right] \ . \tag{4.18}$$

In the balanced-growth equilibrium, the innovation and adaption rates, the relative prices and wage rates and the ratios Φ/H^N and Φ/H^S are constant over time.

The products in each industry follow stochastic life cycles with different patterns. A particular product might be improved several times in succession by various Northern firms before it is adapted by a multinational firm. Then production shifts to the South where the product is manufactured by the multinational firm an perhaps by a competitive-fringe firm later on until being upgraded again by an innovative firm in the North. An appropriate measure of the average length of a North-South cycle is $(1/\ell + 1/h)$. The first term indicates how long, on average, a product will be produced in the North before being adapted by a multinational firm, the second term indicates how long, on average, a product will be manufactured in the South before a further quality innovation occurs.

Globalization and Intellectual Property Rights

The steady-state equilibrium of the model enables us to derive some comparative-static effects of globalization on the dynamics of innovation and adaption.

As in the former model, an increase in size of the South has no impact on the long-run innovation rate h^*. Comparative statics of (4.19) show that $d\ell/dL^S > 0$. Southern countries joining the world trading system have no direct effect on the Northern steady-state condition (4.17), but imply that the ratio Φ/H^S increases for a given value of ℓ in the Southern steady-state condition (4.18). This generates a higher steady-state rate of foreign direct investment ℓ and a higher steady-state value of the ratio Φ/H^S (or Φ/H^N, respectively). The permanent increase in this ratio is associated with a temporary increase in the innovation rate h above its steady-state value h^*.

Proposition 5: *Globalization measured by an increase in the size of the South leads to a temporary increase in the innovation rate and to a permanent increase in the adaption rate so that the average length of a North-South product cycle decreases.*

Furthermore, the adaption rate ℓ depends on the exogenous imitation rate k, which captures the effect of a stronger protection of the intellectual property rights, and parameter η, which measures the difficulty of realizing a technology transfer within a multinational firm. Comparative statics of (4.19) show that $d\ell/dk < 0$ and $d\ell/d\eta < 0$. A decrease in the imitation rate k has no direct effect on the Northern steady-state condition (4.17), but implies that Φ/H^S increases for a given value of ℓ in the Southern steady-state condition (4.18). The latter effect works directly and through a reduction in the North-South wage gap ω as determined in (4.12). This generates a higher steady-state rate of foreign direct investment ℓ and a higher steady-state value of the ratio Φ/H^S (or Φ/H^N, respectively). The permanent increase in this ratio is associated with a temporary increase in the innovation rate h above its steady-state value h^*. A reduction of η, implying less costly opportunities for multinational firms to transfer technologies to Southern affiliates, induces comparative-static effects in the same direction.

Proposition 6: *Stronger protection of intellectual property rights measured by a decline in the imitation rate of the competitive fringe in the South leads to a temporary increase in the innovation rate and to a permanent increase in the rate of technology transfer to the South within multinational firms. Improved conditions for foreign direct investment, measured by a decrease in the difficulty for multinational firms to transfer technology to the South generates similar steady-state equilibrium effects.*

Improved conditions for foreign direct investment provide additional incentives for multinational firms to increase their adaptive R&D activities and transfer production to the lower-wage South faster. The more rapid international technology transfer in turn increases the demand for Southern human capital employed in adaptive research and decreases the demand for human capital in Northern production. These two effects cause a permanent decline in the North-South wage gap and make it more attractive for firms to engage in innovative R&D in the North. Northern firms respond by innovating more frequently such that the difficulty of realizing innovations rises at a higher than usual rate. This increase causes the innovation rate to gradually slow down and to converge to the long-run innovation rate again.

A comparison of the results of this innovation-adaption model to those of the innovation-imitation model analyzed above shows that the mode of international technology transfer is crucial. When technology transfer occurs through imitation of Northern products, stronger intellectual property rights lead to a temporary decrease in the innovation rate and to a permanent increase in the North-South wage gap. The opposite holds when technology transfer is driven by foreign direct investment. In the real world, technology transfer occurs both, within multinational firms via foreign direct investment and across rival firms via imitation. This leads Dinopoulos and Segerstrom (2010, p. 15) to conjecture that the total effect depends on how important each mode of technology transfer is. We agree that the two mechanisms of imitation and adaption complement each other. In order to assess the combined effect of both transfer mechanisms, Sener (2006) has attempted to formulate a unified model. Unfortunately, such a generalized model is no longer analytically solvable. Nevertheless, his numerical solutions are in accordance with the results derived in the more restrictive models analyzed in this paper.

5 Summary and Conclusion

We have presented a class of dynamic general-equilibrium models of education, innovation and international technology transfer to explain the dynamics of industrial evolution and aggregate growth. Recent semi-endogenous models of closed and open economies have accomplished a valuable task by removing the scale effect present in endogenous growth models of the first generation. A disturbing property of these non-scale models is, however, that the innovation and per-capita growth rates depend proportionally on population growth. This property is clearly at odds with the empirical evidence.

We have offered an alternative interpretation of labor by pointing out the importance of education and human-capital accumulation. The skill acquisition of workers has not only a direct effect on economic growth but also an indirect effect via an acceleration of the innovation processes. The effectiveness of the educational system is therefore most important for the dynamics of innovation and growth. The scale effect is eliminated by the assumption that the realization of innovations becomes more difficult as the products climb up the quality ladders, but this deterioration of technological opportunities is compensated by an improvement of the workers' skills. Education and innovation appear as the two in-line engines of endogenous scale-invariant growth.

The industrial dynamics induced by innovation and international technology transfer correspond to those derived by the semi-endogenous growth models. Globalization by Southern countries joining the world trading system lead to a temporary increase of the innovation rates and to a permanent increase in the imitation or adaption rates. The effects of stronger intellectual property rights depend crucially on the mode of international technology transfer. In case of imitation across rival firms, stronger protection induces a temporary decrease in innovation and a higher North-South wage gap. In case of technology adaption within multinational firms the opposite holds.

As several empirical studies have pointed out, both modes of international technology transfer are important. Our results concerning technology adaption via foreign direct investment describe the dynamics in the consumer electronics industry and the office machinery industry since the 1960s very well. However, more recently the rapid advances in the technological capabilities of engineers in the newly industrialized (Southern) countries have made imitation an even more important channel for international technology transfer. In the personal computer industry, for instance, product cycles have been characterized not only by increasing offshore production by multinational firms which originally developed the computers, but also by imitations realized by competitors in the less developed South. The copies themselves, however, have again been replaced by superior computers and laptops developed by Northern firms. This evidence suggests the formulation of more general models appropriate to analyze the different modes of technology transfer within a single unified framework. This challenging task is left for future research.

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