Iordanis Petsas

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Iordanis Petsas[1]
Department of Economics and Finance, Kania School of Management, University of Scranton, Scranton, PA., USA

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Abstract

This paper develops a simple model of trade and "quality-ladders" growth without scale effects to study the implications of general purpose technologies (GPTs) for international trade. GPTs refer to a certain type of drastic innovations, such as electrification, the transistor, and the Internet, that are characterized by the pervasiveness in use, innovational complementarities, and technological dynamism. The model presents a two-country (Home and Foreign) dynamic general equilibrium framework and incorporates GPT diffusion within Home that exhibits endogenous Schumpeterian growth. The model analyzes the long-run and transitional dynamic effects of a new GPT on the pattern of trade and relative wages. The main findings of the paper are: 1) when the GPT diffusion across industries is governed by *S*-curve dynamics, there are two steady-state equilibria: the initial steady-state arises before the adoption of the new GPT and the final one is reached after the GPT diffusion process has been completed, 2) when all industries at Home have adopted the new GPT, Home enjoys comparative advantage in a greater range of industries compared to Foreign, 3) during the transitional dynamics, Foreign gains back its competitiveness in some of the industries that lost its comparative advantage to Home.

Keywords: general purpose technologies, Schumpeterian growth, comparative advantage, scale effects, R&D races
JEL: F1, F43, O3, O4, L1, L2

Introduction

In any given economic "era" there are major technological innovations, such as electricity, the transistor, and the Internet, that have a far-reaching and prolonged impact. These drastic innovations induce a series of secondary incremental innovations. The introduction of the transistor, for example, triggered a sequence of secondary innovations, such as the development of the integrated circuit and the microprocessor, which are also considered drastic innovations. These main technological innovations are used in a wide range of different sectors inducing further innovations. For example, microprocessors are now used in many everyday products like telephones, cars, personal computers, and so forth.

Even though the distinction between a drastic innovation and the incremental one is quite important to understand the proper roles of technological innovations as engines of growth and trade, economists have paid relatively less attention to the former. Bresnahan and Trajtenberg [1995] christened these types of drastic innovations "General Purpose Technologies" (GPTs henceforth). A GPT is a certain type of drastic innovation which is characterized by the pervasiveness in use (generality of purpose), innovational complementarities, and inherent potential for technical improvement.

Several empirical studies have documented the cross-industry pattern of diffusion for a number of GPTs.[2] In addition, a strand of empirical literature has established that the cross-industry diffusion pattern of GPTs is similar to the diffusion process of product-specific innovations and it is governed by standard *S*-curve dynamics.[3] In other words, the internal-influence epidemic model can provide an empirically-relevant framework to analyze the dynamic effects of a GPT. During this diffusion process, these drastic innovations could generate growth fluctuations and even business cycles.

Second, the dynamic effects of these GPTs take a long period of time to materialize. For instance, David [1990] describes a phase of twenty-five years in the case of the electric dynamo. He argues that the observed productivity slowdown in the earlier stage of electrification and computerization was due to the adjustment process associated with the adoption of a new GPT. Third, these GPTs act as "engines of growth". As a better GPT becomes available, it gets adopted by an increasing number of user industries and fosters complementary advances that raise the industry's productivity growth. As the use of a GPT spreads throughout the economy, its effects become significant at the aggregate level, thus affecting overall productivity growth. In his presidential address to the American Economic Association, Jorgenson [2001] documents the role of information technology in the resurgence of U.S. growth in the late 1990 s.[4] There is plenty of evidence that the rise in structural productivity growth in the late 1990 s can be traced to the introduction of personal computers and the acceleration in the price reduction of semiconductors, which constituted the necessary building blocks for the information technology revolution.[5]

The growth effects of GPTs have been analyzed formally by Helpman and Trajtenberg [1998a]. They emphasize the lost output that occurs because the GPT does not arrive ready to use but requires the invention of a set of complementary components. Petsas [2003] analyzes the dynamic effects of GPTs within a quality-ladders model of scale-invariant Schumpeterian growth. He discusses the transitional dynamics and the long-run equilibrium. Along the transition path, the measure of industries that adopt the new GPT increases, consumption per capita falls, and the interest rate rises.

All the above-mentioned models use a closed economy setup that does not allow them to explain the effects of a drastic innovation technological innovation on international aspects of the economy, such as the pattern of trade, relative wages, and economic growth differences across countries.

Chung and Hwang [2009] examined the open-economy implications of a GPT using the framework developed by Helpman and Trajtenberg [1998a]. They showed that with the introduction of GPTs into the world economy, the developing countries temporarily gain competitiveness in marginal final good industries but end up losing those industries again as a sufficient number of intermediate goods for the new GPT are created in the developed countries.

However, Chung and Hwang's model [2009] exhibits the scale effect property: if one incorporates population growth in these models, then the size of the economy (scale) increases exponentially over time, R&D resources grow exponentially, and so does the long-run growth rate of per-capita real output. Petsas [2010] develops a model of trade based on "quality-ladders" growth without scale effects and analyzes how the pattern of trade and the relative wage are determined in steady-state equilibrium.

The scale effects property is a consequence of the assumption that the growth rate of knowledge is directly proportional to the level of resources devoted to R&D. Jones [1995a] has argued that the scale effects property of earlier endogenous growth models is inconsistent with post-war time series evidence from all major advanced countries that shows an exponential increase in R&D resources and a more-or-less constant rate of per-capita GDP growth. Jones's criticism has stimulated the development of a new class of models that generate growth without scale effects. However, the theoretical literature on trade and growth without scale effects has focused either on closed economy models or on structurally identical economies engaging in trade with each other.[6] This paper develops a two-country general equilibrium framework without scale effects to determine the effect of the introduction of a GPT on the equilibrium relative wages and the pattern of trade between countries.

My approach borrows from Taylor's work [1993] in that industries differ in production technologies. In his model, industries also differ in research technologies and in the set of technological opportunities available for each industry. In the presence of heterogeneous research technologies (captured by different productivity in R&D services), the pattern of R&D production and the pattern of goods production within each country can differ.

As a result, there is a case for trade between countries in R&D services. The absence of heterogeneity in research technologies in my model makes the removal of scale effects more tractable, but eliminates the need for trade in R&D services between countries.

In the present model, there are two countries that may differ in relative size: Home and Foreign. The population in each country grows at a common positive and exogenously given rate and labor is the only factor of production. There is a continuum of industries producing final consumption goods. Labor in each industry can be allocated between the two economic activities, manufacturing of high-quality goods and R&D services, which are used to discover new products of higher quality. As in Grossman and Helpman's [1991a] version of the quality-ladders growth model, the quality of each final good can be improved through endogenous innovation.

The arrival of innovations in each industry is governed by a memoryless Poisson process whose intensity depends positively on R&D investments and negatively on the rate of difficulty of conducting R&D. In order to remove the scale effects property, I consider the permanent effects of growth (PEG) specification that it has been proposed by Dinopoulos and Thompson [1996]. According to this specification, R&D becomes more difficult over time and the degree of R&D difficulty is proportional to the size of the world market.

The analysis in this model generates new findings. The model identifies a unique steady-state equilibrium in the presence of the new GPT, in which the pattern of trade in goods is determined by comparative advantage across industries. In addition and in contrast to earlier work, the model predicts that the pattern of trade is determined by additional factors such as population growth and the R&D difficulty parameter. In contrast to the previous work, factor price equalization is not a property of the equilibrium and there is no trade in R&D services (Proposition 1). With the introduction of a new GPT in the Home country, there are two steady-state equilibria. The industries using the new GPT become more productive making the final goods producers in these industries gain competitiveness (Proposition 2). However, based on the transitional dynamics, the model shows that exists a negative-sloping globally stable-saddle-path. During the transitional dynamics, final goods producers in Foreign start engaging in more R&D and gain back their competitiveness (in both R&D and production) in some of the industries that lost its comparative advantage to Home. (Proposition 3).

The remaining paper is organized as follows. Next section outlines the features of the model. Following section describes the steady state equilibrium of the model and the next one deals with the transitional dynamics. Final section concludes this paper by summarizing the key findings along with policy implications and suggesting possible extensions. The algebraic details and proofs of all propositions in this paper are relegated to the Appendix.

The Model

This section develops a two-country, dynamic, general-equilibrium model with the following features. Each country engages in two activities: the production of final consumption goods and research and development. Each of the two economies is populated by a continuum of industries indexed by $\theta \in [0,1]$. A single primary factor, labor, is used in both goods and R&D production for any industry. In each industry θ firms are distinguished by the quality j of the products they produce. Higher values of j denote higher quality and j is restricted to taking on integer values. At time $t=0$, the state-of-the-art quality product in each industry is $j=0$, that is, some firm in each industry knows how to produce a $j=0$ quality product and no firm knows how to produce any higher quality product. The firm that knows how to produce the state-of-the-art quality product in each industry is the global leader for that particular industry. At the same time, challengers in both countries engage in R&D to discover the next higher-quality product that would replace the global leader in each industry. If the state-of-the-art quality in an industry is j, then the next winner of an R&D race becomes the sole global producer of a j+1 quality product. Thus, over time, products improve as innovations such as push each industry up its "quality ladder," as in Grossman and Helpman [1991a].

I assume for simplicity, that all firms in the global economy know how to produce all products that are at least one step below the state-of-the-art quality product in each industry. This assumption, which is standard in most quality-ladders growth models, prevents the incumbent monopolist from engaging in further R&D, which is also standard assumption in most quality-ladder models.

For clarity, I adopt the following conventions regarding notation. Henceforth, superscripts "h" and "f" identify functions and variables of "Home" and "Foreign" countries, respectively. Functions and variables without superscripts are related to the global economy, while functions and variables with subscripts are related to activities and firms within an industry.

Introduction and Diffusion of a New GPT

The introduction of a new GPT and its diffusion path is modeled as follows: The world economy has achieved a steady-state equilibrium, manufacturing final consumption goods with an old GPT. I begin the analysis at time $t = t_0$, when a new GPT arrives at Home unexpectedly. Firms in each industry start adopting the new GPT at an exogenous rate.

At Home, at each point in time, a fraction of industries, η, uses the new GPT and a fraction of industries, $(1-\eta)$, does not use the new GPT. For example, if the old GPT is the steam power and the new GPT is electricity, η industries use electricity in their production and $(1-\eta)$ industries use steam power in their production.[7]

I use the epidemic model to describe the diffusion of a new GPT across the continuum of industries.[8] Its form can be described by the following differential equation,

$$\frac{\dot{\eta}}{\eta} = \delta(1-\eta)\,, \tag{1}$$

where $\dot{\eta} = \partial\eta/\partial t$ denotes the rate of change in the fraction of industries that use the new GPT and $\delta > 0$ is the rate of diffusion. Equation (1) states that the number of new adoptions during the time interval dt, $\dot{\eta}$, is equal to the number of remaining potential adopters, $(1-\eta)$, multiplied by the probability of adoption, which is the product of the fraction of industries that have already adopted the new GPT, η, and the parameter δ, which depends upon factors such as the attractiveness of the innovation and the frequency of adoption, both of which are assumed to be exogenous.

The solution to equation (1) expresses the measure of industries that have adopted the new GPT as a function of time and yields the equation of the sigmoid (*S*-shaped) logistic curve:

$$\eta = \frac{1}{[1+e^{-(\varphi+\delta t)}]}\,, \tag{2}$$

where φ is the constant of integration. Notice that for $t \to \infty$, equation (2) implies that all industries located at Home have adopted the new GPT.[9]

Household Behavior

Let $N^i(t)$ be country i's population at time t. I assume that each country's population is growing at a common constant, exogenously given rate $g_N = \dot{N}^i(t)/N^i(t) > 0$. In each country there is a continuum of identical dynastic families that provide labor services in exchange for wages, and save by holding assets of firms engaged in R&D. Each individual member of a household is endowed with one unit of labor, which is inelastically supplied. I normalize the measure of families in each country at time 0 to equal unity. Thus, the population of workers at time t in country i is $N(t)^i = e^{g_N t}$.

Each household in country i maximizes the discounted utility[10]

$$U = \int_0^\infty e^{-(\rho-g_N)t} \log u(t)\,dt\,, \tag{3}$$

where $\rho > 0$ is the constant subjective discount rate. In order for U to be bounded, I assume that the effective discount rate is positive (i.e., $\rho - g_N > 0$). Expression log u(t) captures the per capita utility at time t, which is defined as follows:

$$\log u(t) \equiv \int_0^1 \log[\sum_j \lambda^j q(j,\theta,t)]\,d\theta\,. \tag{4}$$

In equation (4), q(j, θ, t) denotes the quantity consumed of a final product of quality j (i.e., the product that has experienced j quality improvements) in industry $\theta \in [0,1]$ at time t. Parameter $\lambda > 1$ measures the size of quality improvements (i.e., the size of innovations).

At each point in time t, each household allocates its income to maximize (4) given the prevailing market prices. Solving this optimal control problem yields a unit elastic demand function for the product in each industry with the lowest quality-adjusted price

$$q^i(j,\theta,t) = \frac{c^i(t)N^i(t)}{p^i(t)}, \tag{5}$$

where $c^i(t)$ is country i's per capita consumption expenditure, and $p(t)$ is the market price of the good considered. Because goods within each industry adjusted for quality are by assumption identical, only the good with the lowest quality-adjusted price in each industry is consumed. The quantity demanded of all other goods is zero. The global demand for a particular product is given by aggregating equation (5) across the two countries to obtain

$$q(j,\theta,t) = \sum_{i=h,f} q^i(j,\theta,t). \tag{6}$$

Given this static demand behavior, the intertemporal maximization problem of country i's representative household is equivalent to

$$\max_{c^i(t)} \int_0^{\infty} e^{-(\rho - g_N)t} \log c^i(t) dt, \tag{7}$$

subject to the intertemporal budget constraint $\dot{a}^i(t) = r^i(t)a(t) + w^i(t) - c^i(t) - g_N a^i$, where $a^i(t)$ denotes the per capita financial assets in country i, $w^i(t)$ is the wage income of the representative household member in country i, and $r^i(t)$ is country i's instantaneous rate of return at time t. The solution to this maximization problem obeys the well-known differential equation

$$\frac{\dot{c}^i(t)}{c^i(t)} = r^i(t) - \rho, \tag{8}$$

Equation (8) implies that a constant per-capita consumption expenditure is optimal when the instantaneous interest rate in each country equals the consumer's subjective discount rate ρ. I normalize total consumer spending to equal a constant value E at each point in time, and I choose for simplicity

$$E = 1. \tag{9}$$

This normalization implies that the value of output equals one at each point in time and combined with the differential equation for consumption expenditure per capita it implies that the nominal interest rate r equals the subjective discount rate

$$r(t) = \rho \quad \text{for all t.} \tag{10}$$

Product Markets

In each country firms can hire labor to produce any final consumption good $\theta \in [0,1]$. Let $L^i(\theta, t)$ and $Q^i_\varsigma(\theta, t)$ respectively denote the amounts of labor devoted in manufacturing of final consumption good θ in country i and the output of final consumption good θ in country i produced with the aid of the $\varsigma \in \{0,1\}$ GPT. Then the production function of the final consumption good θ in country i is given by the following equation

$$Q^i_\varsigma(\theta,t) = \frac{L^i(\theta,t)}{\alpha^i_Q(\theta)\gamma_\varsigma}, \tag{11}$$

where $\alpha^i_Q(\theta)$ is the unit labor requirement associated with the final consumption good θ in country i and γ_ς captures the productivity gains associated with the new GPT and equals to

$$\gamma_\varsigma = \begin{cases} \gamma_1 = \gamma \prec 1 & \forall \theta \in [0,\eta] \\ \gamma_0 = 1 & \forall \theta \in [\eta,1] \end{cases}. \tag{12}$$

I assume that each vertically differentiated good must be manufactured in the country in which the most recent product improvement has taken place. That is, I rule out international licensing and multinational corporations.[11]

Following Dornbusch et al. [1977], the relative labor unit requirement for each good θ is given by

$$A(\theta) \equiv \frac{\alpha^f_Q(\theta)}{\alpha^h_Q(\theta)} \quad A'(\theta) < 0 \tag{A.1}$$

The relative unit labor requirement function in (A.1) is by assumption continuous, and decreasing in θ.

The assumptions that goods within an industry are identical when adjusted for quality and Bertrand price competition in product markets imply that the monopolist in each industry engages in limit pricing. The assumption that the technology of all inferior quality products is public knowledge imply that the quality leader charges a single price, which is λ times the lowest manufacturing cost between the two countries:

$$p = \lambda \min\left\{ \alpha^h_Q(\theta) w^h, \alpha^f_Q(\theta) w^f \right\}. \tag{13}$$

I assume that if for any industry θ, its manufacturing unit cost is lower in Foreign than in Home, $w^f \alpha^f_Q(\theta) < w^h \alpha^h_Q(\theta)$, then $w^f \alpha^f_Q(\theta) < w^h \alpha^h_Q(\theta)\gamma$ also holds.

I also assume that the wage of home labor, w^h, is greater than the wage of foreign labor, w^f. That is, the home relative wage, ω, is greater than one[12]

$$\omega = \frac{w^h}{w^f} > 1. \tag{14}$$

The last two assumptions imply that the price of every top quality good is equal to

$$p = \lambda \alpha_Q^f(\theta) w^f. \tag{15}$$

It follows that the stream of profits of the incumbent monopolist that uses the $\varsigma \in \{0,1\}$ GPT and produces the state-of-the-art quality product in Home will be equal to

$$\pi_\varsigma^h(\theta,t) = [\lambda w^f \alpha_Q^f(\theta) - w^h a_Q^h(\theta)\gamma_\varsigma]q = \left(1 - \frac{\omega \alpha_Q^h(\theta)\gamma_\varsigma}{\lambda \alpha_Q^f(\theta)}\right) N(t), \tag{16}$$

while the stream of profits of the incumbent monopolist that produces the state-of-the-art quality product in Foreign will be equal to

$$\pi^f(\theta,t) = [\lambda \alpha_Q^f(\theta) - w^f a_Q^f(\theta)]q = \frac{(\lambda - 1)}{\lambda} N(t), \tag{17}$$

where $N(t) = [N^h(t) + N^f(t)]$ is the size of world population and the world expenditure on final consumption goods.

R&D Races

Labor is the only input engaged in R&D in any industry $\theta \in [0,1]$. Let $L_R^i(\theta,t)$ and $R^i(\theta,t)$ respectively denote the amounts of labor devoted in R&D services in industry θ in country i and the output of R&D services in industry θ in country i. The production function of R&D services in industry θ in country i exhibits constant returns and is given by the following equation[13]

$$R^i(\theta,t) = \frac{L_R^i(\theta,t)}{\alpha_R}, \tag{18}$$

where α_R is the unit labor requirement in the production of R&D services. Note that the absence of a superscript and the absence of the industry index θ in the unit labor requirement imply that they are the same across countries, industries and goods of different quality levels. The absence of heterogeneous research technologies allows me to focus on the implications of assumption (A.1) on the properties of the model.[14]

In each industry θ there are global, sequential and stochastic R&D races that result in the discovery of higher-quality final products. A challenger firm k that is located in country $i \in \{h,f\}$ targeting a quality leader in country $i \in \{h,f\}$ engages in R&D in industry θ and discovers the next higher-quality product with instantaneous probability $I_k^i(\theta,t)dt$, where dt is an infinitesimal interval of time and

$$I_k{}^i(\theta,t)=\frac{R_k^i(\theta,t)}{X(t)}, \tag{19}$$

where $R_k^i(\theta,t)$ denotes firm k's R&D outlays and X (t) captures the difficulty of R&D in industry θ at time t. I assume that the returns to R&D investments are independently distributed across challengers, countries, industries, and over time. Therefore, the industry-wide probability of innovation can be obtained from equation (19) by summing up the levels of R&D across all challengers in that country. That is,

$$I^i(\theta,t)=\sum_k I_k^i(\theta,t)=\frac{R^i(\theta,t)}{X(t)}, \tag{20}$$

where $R^i(\theta,t)$ denotes total R&D services in industry θ in country i. Variable $I^i(\theta, t)$ is the effective R&D.[15] The arrival of innovations in each industry follows a memoryless Poisson process with intensity $I(\theta,t)=\sum_i R^i(\theta,t)/X(t)$ which equals the global rate of innovation in a typical industry. The function X (t) has been introduced in the endogenous growth literature after Jone's [1995a] empirical criticism of R&D based growth models generating scale effects.

A recent body of theoretical literature has developed models of Schumpeterian growth without scale effects.[16] Two alternative specifications have offered possible solutions to the scale-effects property. The first specification proposed by Dinopoulos and Thompson [1996] removes the scale-effects property by assuming that the level of R&D difficulty is proportional to the market size measured by the level of population,

$$X(t) = kN(t), \tag{21}$$

where $k > 0$ is a parameter.

This specification captures the notion that it is more difficult to introduce new products and replace old ones in a larger market.[17] The model that results form this specification is called the permanent effects of growth (PEG) model because policies such as an R&D subsidy and tariffs can alter the per-capita long-run growth rate.[18]

Consider now the stock-market valuation of temporary monopoly profits. Consumer savings are channeled to firms engaging in R&D through the stock market. The assumption of a continuum of industries allows consumers to diversify the industry-specific risk completely and earn the market interest rate. At each instant in time, each challenger issues a flow of securities that promise to pay the flow of monopoly profits if the firm wins the R&D race and zero otherwise.[19] Consider now the stock-market valuation of the incumbent firm in each industry. Let $V_\varsigma^i(t)$ denote the expected global discounted profits of a successful innovator at time t in country i, when the global monopolist uses the $\varsigma\in\{0,1\}$ GPT and charges a price p for the state-of-the-art quality product. Because each global quality leader is targeted by challengers from both countries who engage in R&D to discover the next higher-quality product, a shareholder faces a capital loss $V^i_\varsigma(t)$ if further innovation occurs. The event that the next innovation will arrive occurs with instantaneous probability Idt, whereas the event that no innovation will arrive occurs with instantaneous probability 1-Idt. Over a time interval dt, the shareholder of an incumbent's stock receives a dividend $\pi(t)dt$ and the value of the incumbent appreciates by $dV^i_\varsigma(t)=[\partial V^i_\varsigma(t)/\partial t]dt=\dot{V}^i_\varsigma(t)dt$. Perfect international capital mobility implies that $r^h=r^f=r$. The absence of profitable arbitrage opportunities requires the expected rate of return on stock issued by a successful innovator to be equal to the riskless rate of return r; that is,

$$\frac{\dot{V}^i_\varsigma(\theta,t)}{V^i_\varsigma(\theta,t)}[1-I(\theta,t)dt]dt+\frac{\pi^i_\varsigma(\theta,t)}{V^i_\varsigma(\theta,t)}dt-\frac{[V^i_\varsigma(\theta,t)-0]}{V^i_\varsigma(\theta,t)}I(\theta,t)dt=rdt. \quad (22)$$

Taking limits in equation (22) as $dt\rightarrow 0$ and rearranging terms appropriately gives the following expression for the value of monopoly profits

$$V^i_\varsigma(\theta,t)=\frac{\pi^i_\varsigma(\theta,t)}{\rho+I(\theta,t)-\dfrac{\dot{V}^i_\varsigma(\theta,t)}{V^i_\varsigma(\theta,t)}}. \quad (23)$$

A typical challenger k located in country i chooses the level of R&D investment $R^i_k(\theta,t)$ to maximize the expected discounted profits

$$V^i_\varsigma(\theta,t)\frac{R^i_k(\theta,t)}{X(t)}dt-w^i\alpha_R R^i_k(\theta,t)dt, \quad (24)$$

where $I^i_k dt=[R^i_k(\theta,t)/X(t)]dt$ is the instantaneous probability of discovering the next higher-quality product and $w^i\alpha_R R^i_k(\theta,t)$ is the R&D cost of challenger k located in country i.

Free entry into each R&D race drives the expected discounted profits of each challenger down to zero and yields the following zero profit condition:

$$V^i_\varsigma(t)=w^i\alpha_R X(t). \quad (25)$$

The pattern of R&D production across the two countries can be determined by utilizing equations (23) and (25). Combining these equations and evaluating them at the margin I can obtain the R&D schedule (i.e., the schedule of relative labor productivities in goods) as follows

$$\omega=RD(\tilde{\theta})=\frac{\alpha^f_Q(\tilde{\theta})}{\alpha^h_Q(\tilde{\theta})\gamma_\varsigma}, \quad (26)$$

where $RD(\tilde{\theta})$ is continuous and decreasing in $\tilde{\theta}$. For low values of θ, Home has higher relative labor productivity than Foreign, and thus it earns higher wage. Therefore, Home has comparative advantage in producing and conducting R&D the final goods with lower θ and Foreign has comparative advantage in producing and conducting R&D the final goods with higher θ. The R&D schedule can be depicted in Figure 1.

Lemma 1: *Under assumption* (A.1) *and for any given value of the relative wage,* $\omega \in \left(\alpha_Q^f(1)/\alpha_Q^h(1), \alpha_Q^f(0)/\alpha_Q^h(0)\right)$, *there exists an industry* $\tilde{\theta}$ *defined by equation* (26) *such that*

(a) *firms are indifferent between conducting R&D in Foreign or in Home*,

(b) *for each industry* $\theta \in [0, \tilde{\theta})$, *only Home conducts R&D*,

(c) *for each industry* $\theta \in (\tilde{\theta}, 1]$, *only Foreign conducts R&D*.

The results in Lemma 1 are based on the zero-profit conditions in the R&D sector. Dornbusch et al. [1977] derive the same results found in Lemma 1 under the assumption of perfect competition in all markets. In the present model, if in industry θ, R&D is undertaken by Home, then the zero profit conditions for R&D imply that Foreign has negative profits in this particular industry (see equations (23) and (25)). Since firms located in the Home country have higher discount profits than foreign firms for the goods in the range $\theta \in [0, \tilde{\theta})$, this prevents challengers from the Foreign country to finance their R&D costs in the range of industries $\theta \in [0, \tilde{\theta}]$ and thus choose not to engage in R&D (since this would yield negative profits). The reverse is true for those industries that Foreign undertakes R&D. Home has negative profits in the industries $\theta \in (\tilde{\theta}, 1]$, so it does not pay off to engage in R&D in those industries. Thus, both countries will develop and sustain their comparative advantage in the industries they conduct their R&D.

Labor Markets

Consider first the Home labor market. All workers are employed by firms in either production or R&D activities. Taking into account that each industry leader charges the same price p and that consumers only buy goods from industry leaders in equilibrium, it follows from (11) that employment of labor in the production of goods using the new GPT in Home is $\int_0^{\eta} Q^h(\theta,t)\alpha_Q^h \gamma d\theta$, while employment of labor in the production of goods using the old GPT is $\int_{\eta}^{\tilde{\theta}} Q^h(\theta,t)\alpha_Q^h d\theta$. Solving equation (18) for each industry leader's R&D employment $L_R^h(\theta, t)$ and then integrating across industries, total R&D employment by industry leaders in the home country is $\int_0^{\tilde{\theta}} R^h(\theta,t)\alpha_R d\theta$. Thus, the full employment of labor condition for the home country at time t is given by

$$N^h(t)=\int_0^{\eta} Q^h(\theta,t)\alpha_Q^h(\theta)\gamma d\theta+\int_{\eta}^{\tilde{\theta}} Q^h(\theta,t)\alpha_Q^h d\theta+\int_0^{\tilde{\theta}} R^h(\theta,t)\alpha_R d\theta. \tag{27}$$

The full employment of labor condition for the foreign country at time t is given by

$$N^f(t)=\int_{\tilde{\theta}}^{1} Q^f(\theta,t)\alpha_Q^f(\theta)d\theta+\int_{\tilde{\theta}}^{1} R^f(\theta,t)\alpha_R d\theta \ . \tag{28}$$

Equations (27) and (28) complete the description of the model.

Steady-State Equilibrium

In this section I derive the steady-state equilibrium. Assuming that the relative wage, ω, is constant over time at the steady-state equilibrium, equation (25) implies that $\dot{V}_{\varsigma}^i(\theta,t)/V_{\varsigma}^i(\theta,t)=\dot{X}(t)/X(t)=g_N$. That is, the expected global discounted profits of a successful innovator at time t in country i, $V_{\varsigma}^i(t)$, and the level of R&D difficulty, X(t), grow at the constant rate of population growth, g_N. Combining equations (23) and (25) after taking into account equations (16) and (17), I obtain the following zero profit conditions for Home and Foreign respectively for each industry:

$$\frac{\left(1-\dfrac{\omega\alpha_Q^h(\theta)\gamma}{\lambda\alpha_Q^f(\theta)}\right)}{\rho+I(\theta,t)-g_N}=w^h\alpha_R k \quad \forall\theta\in[0,\eta] \tag{29}$$

$$\frac{\left(1-\dfrac{\omega\alpha_Q^h(\theta)}{\lambda\alpha_Q^f(\theta)}\right)}{\rho+I(\theta,t)-g_N}=w^h\alpha_R k \quad \forall\theta\in[\eta,\tilde{\theta}) \tag{30}$$

$$\frac{\dfrac{(\lambda-1)}{\lambda}}{\rho+I(t)-g_N}=w^f\alpha_R k \ . \quad \forall\theta\in(\tilde{\theta},1] \tag{31}$$

Utilizing equations (29)–(31), one can rank the level of global R&D investment between Home and Foreign. Notice that the level of global R&D investment, I, does not depend on θ for $\theta\in(\tilde{\theta},1]$. On contrast, the level of global R&D investment, I, depends on θ for $\theta\in[0,\tilde{\theta})$. As Home conducts R&D in more industries, the level of global R&D investment increases.

Integrating equation (29) over $[0,\eta]$, equation (30) over $[\eta,\tilde{\theta})$, and equation (31) over $(\tilde{\theta},1]$ I obtain the following zero profit conditions for Home and Foreign, respectively at the economy-wide level:

$$\left(\eta-\frac{\omega\gamma}{\lambda}\int_0^{\eta}\frac{\alpha_Q^h(\theta)}{\alpha_Q^f(\theta)}d\theta\right)=w^h\omega\alpha_R k[\rho+I(\theta,t)-g_N]\eta \tag{32}$$

$$\left(\tilde{\theta}-\eta-\frac{\omega}{\lambda}\int_{\eta}^{\tilde{\theta}}\frac{\alpha_Q^h(\theta)}{\alpha_Q^f(\theta)}d\theta\right)=w^h\omega\alpha_R k[\rho+I(\theta,t)-g_N](\tilde{\theta}-\eta) \tag{33}$$

$$\frac{(\lambda-1)}{\lambda}=w^f\alpha_R k[\rho+I(\theta,t)-g_N], \tag{34}$$

Substitution of equations (5) and (13) into the first integral of equation (27) yields the demand for manufacturing labor in Home

$$\frac{\gamma N(t)}{\lambda w^f}\int_0^{\eta}\frac{\alpha_Q^h(\theta)}{\alpha_Q^f(\theta)}d\theta. \tag{35}$$

Combining equations (18), (20), and (21), one can obtain the demand for R&D labor in Home

$$kN(t)\alpha_R\int_0^{\tilde{\theta}} I^h(\theta,t)d\theta. \tag{36}$$

Given that there is a large number of independent industries, the law of large numbers implies that the integral in equation (33) can be written as follows:

$$\int_0^{\tilde{\theta}} I(\theta,t)d\theta=\tilde{\theta}I(t). \tag{37}$$

where $I(t)=\int_0^1 I(\theta,t)d\theta$ is the average "effective-R&D" of the world economy.

Substituting equations (35) and (37) (after taking into account equation (34)) into Home's full employment of labor condition (equation 27) yields the resource condition

$$\bar{N}^h(t)=\frac{1}{\lambda w^f}\left(\gamma\int_0^{\eta}\frac{\alpha_Q^h(\theta)}{\alpha_Q^f(\theta)}d\theta+\int_{\eta}^{\tilde{\theta}}\frac{\alpha_Q^h(\theta)}{\alpha_Q^f(\theta)}d\theta\right)+k\alpha_R\tilde{\theta}I(t), \tag{38}$$

where $\bar{N}^h(t)\equiv N^h(t)/N(t)$ is Home's population size relative to the world population size.

Similar substitutions yield the resource condition for the foreign country:

$$\bar{N}^f(t) = \frac{(1-\tilde{\theta})}{\lambda w^f} + k\alpha_R(1-\tilde{\theta})I(t), \tag{39}$$

where $\bar{N}^f(t) \equiv N^f(t)/N(t)$ is the foreign country's population relative to the world population.

The above resource conditions described by equations (38) and (39) hold at each instant in time because, by assumption, factor markets clear instantaneously in both countries.

Equations (32), (33), (34), along with equations (38) and (39) yield a second schedule in (θ,ω) space, the mutual resource schedule[20]

$$\omega = MR(\tilde{\theta}) = \frac{\left(\frac{\bar{N}^f}{(1-\tilde{\theta})} + k\alpha_R(\rho - g_N)\right)\tilde{\theta}}{\bar{N}^h + \tilde{\theta}k\alpha_R(\rho - g_N)}. \tag{40}$$

The mutual resource schedule states that the relative wage ω, which clears labor markets in both countries, is an increasing function of the range of goods $\tilde{\theta}$ produced in Home. If the range of goods produced by Home increases, Home's relative demand for labor (both in manufacturing and R&D) increases. The excess demand for labor drives the level of the relative wage higher.

The mutual resource condition (MR) can be depicted in Figure 1. The vertical axis measures the home country's relative wage, ω, and the horizontal axis reflects the measure of industries, θ. The intersection of the downward sloping RD ($\tilde{\theta}$) schedule and the upward sloping MR ($\tilde{\theta}$) schedule at point E determines the steady-state equilibrium relative wage, ω, and the marginal industry $\tilde{\theta}$ in which both countries undertake production in goods and R&D services.[21]

Therefore, I arrive at:

Proposition 1: *For sufficiently large* $\bar{N}^f/\bar{N}^h$*, there exists a unique steady-state equilibrium such that*

(a) *Home's relative wage,* ω*, is greater than one,*

(b) *Home has a sustained comparative advantage in the range of industries* $\theta \in [0,\tilde{\theta})$. *In each industry* $\theta \in [0,\tilde{\theta})$, *only Home conducts R&D, produces, and exports the state of the-art product,*

(c) *Foreign has a sustained comparative advantage in the range of industries* $\theta \in (\tilde{\theta},1]$. *In each industry* $\theta \in (\tilde{\theta},1]$, *only Foreign conducts R&D, produces, and exports the state of the-art product.*

(d) *Home uses the new GPT in the range of industries* $\theta \in [0,\eta]$ *and uses the old GPT in the range of industries* $\theta \in [\eta,\tilde{\theta}]$.

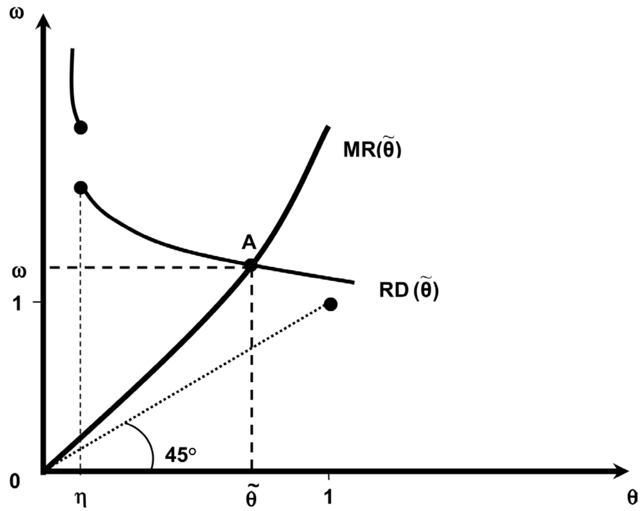
The results from this proposition can be found in other models. The static continuum Ricardian model developed by Dornbusch et al. [1977] and the dynamic learning-by-doing model introduced by Krugman [1987] produce similar features with the equilibrium depicted in Figure 1.

Figure 1 illustrates the steady-state equilibrium in the presence of the new GPT. The pattern of trade in goods is determined by comparative advantage across industries. In addition and in contrast to earlier work, the model predicts that the pattern of trade is determined by additional factors such as population growth and the R&D difficulty parameter. Moreover, the absence of heterogeneity in research technologies results in no trade in R&D services. Taylor [1993], has introduced heterogeneity in research technologies and result in an equilibrium with trade in R&D services. Finally, factor price equalization is not a property of the equilibrium depicted in Figure 1.

Proposition 2: *If η is governed by S-curve dynamics, there are two steady-state equilibria: the initial steady-state equilibrium arises before the adoption of the new GPT, where $\eta = 0$, and the final steady-state equilibrium is reached after the diffusion process of the new GPT has been completed, where $\eta = 1$. At the final steady-state equilibrium: Home produces, conducts R&D, and exports more goods, $\tilde{\theta}(1) > \tilde{\theta}(0)$, Home's relative wage is higher, $\omega(1) > \omega(0)$.*

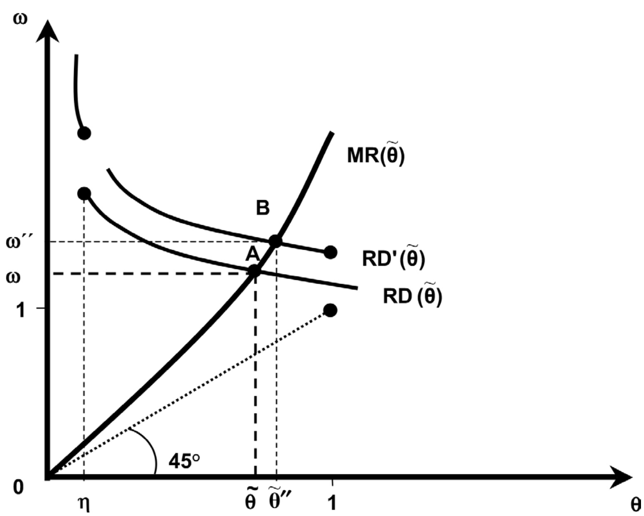
These comparative steady-state properties can be illustrated with the help of Figure 2. Before the introduction of the new GPT in Home, the world economy is in a steady state (point A) where $\eta = 0$, with Home exporting the range of goods $\tilde{\theta}(0)$, and with its relative wage given by $\omega(0)$. The new GPT arrives in the world economy at time $t = 0$ with a given measure of industries $\eta > 0$. Thus, at time $t = 0$, a portion of the RD schedule jumps upward for those industries that are using the new GPT, since these industries are now more productive due to new GPT. An increase in the measure of industries that adopt the new GPT makes the RD schedule in Figure 2 shift upward from RD (where $\eta = 0$) to RD′ (where $\eta = 1$) resulting in higher relative wage and in higher comparative advantage for Home. In other words, when all industries at Home have adopted the new GPT, final goods producers in Home gain competitiveness. The new steady state is at point B, where $\eta = 1$, with Home exporting the range of goods $\tilde{\theta}''$ and with its relative wage given by ω''.

FIGURE 1. Steady-State Equilibrium before the introduction of the new GPT



Source: own elaboration.

FIGURE 2. Steady-State Equilibria
Point A: No industry has adopted the new GPT
Point B: All industries have adopted the new GPT



Source: own elaboration.

Transitional Dynamics

In this section I analyze the transitional dynamics of the model. I use the time-elimination method described by Mulligan and Sala-i-Martin [1992].[22] The equation that governs the GPT diffusion (1) together with equations (20) and (22) (which hold at each instant of time) enable me to construct a system of two differential equations that govern the evolution of $\tilde{\theta}$ and η. By proper substitutions, I obtain:

$$\frac{\left(1-\frac{\omega\alpha_Q^h(\theta)\gamma}{\lambda\alpha_Q^f(\theta)}\right)}{\rho+I(\theta,t)-(g_{w^h}+g_N)}=w^h\alpha_R k \quad \forall\theta\in[0,\eta] \tag{41}$$

$$\frac{\left(1-\frac{\omega\alpha_Q^h(\theta)}{\lambda\alpha_Q^f(\theta)}\right)}{\rho+I(\theta,t)-(g_{w^h}+g_N)}=w^h\alpha_R k \quad \forall\theta\in[\eta,\tilde{\theta}] \tag{42}$$

$$\frac{\frac{(\lambda-1)}{\lambda}}{\rho+I(\theta,t)-(g_{w^f}+g_N)}=w^f\alpha_R k \quad \forall\theta\in[\tilde{\theta},1] \tag{43}$$

Integrating equations (41)–(43), I obtain:

$$\left(\eta-\frac{\omega\gamma}{\lambda}\int_0^{\eta}\frac{\alpha_Q^h(\theta)}{\alpha_Q^f(\theta)}d\theta\right)=w^h\omega\alpha_R k[\rho+I(\theta,t)-g_{w^h}+g_N]\eta \tag{44}$$

$$\left(\tilde{\theta}-\eta-\frac{\omega}{\lambda}\int_{\eta}^{\tilde{\theta}}\frac{\alpha_Q^h(\theta)}{\alpha_Q^f(\theta)}d\theta\right)=w^h\omega\alpha_R k[\rho+I(\theta,t)-g_{w^h}-g_N](\tilde{\theta}-\eta) \tag{45}$$

$$\frac{(\lambda-1)}{\lambda}=w^f\alpha_R k[\rho+I(\theta,t)-g_{w^f}-g_N], \tag{46}$$

Manipulating equations (44) and (45), yields:

$$\int_{\eta}^{\tilde{\theta}}\frac{\alpha_Q^h(\theta)}{\alpha_Q^f(\theta)}d\theta=\frac{(\tilde{\theta}-\eta)\gamma}{\eta}\int_0^{\eta}\frac{\alpha_Q^h(\theta)}{\alpha_Q^f(\theta)}d\theta \tag{47}$$

Taking logs and differentiate in equation (47) yields:

$$\frac{\dot{\tilde{\theta}}}{\tilde{\theta}}=\frac{\left(\eta\alpha_Q^h(\eta)(\tilde{\theta}-\eta)(A_1(\eta)+A_2(\tilde{\theta},\eta))-A_1(\eta)A_2(\tilde{\theta},\eta)\alpha_Q^f(\eta)\tilde{\theta}\right)\alpha_Q^f(\tilde{\theta})\delta(1-\eta)}{\tilde{\theta}A_1(\eta)\alpha_Q^f(\eta)[\alpha_Q^h(\tilde{\theta})(\tilde{\theta}-\eta)-\alpha_Q^f(\tilde{\theta})A_2(\tilde{\theta},\eta)]} \tag{48}$$

where

$$A_1(\eta)=\int_0^{\eta}\frac{\alpha_Q^h(y)}{\alpha_Q^f(y)}dy \quad \text{and} \quad A_2(\tilde{\theta},\eta)=\int_{\eta}^{\tilde{\theta}}\frac{\alpha_Q^h(y)}{\alpha_Q^f(y)}dy$$

Equations (48) and (1) determine the evolution of the two endogenous variables of the model, the range of goods Home exports, $\tilde{\theta}$, and the number of industries at Home that have adopted the new GPT, η.

Equation (48) is equal to zero, when $\eta = 1$, or when the following condition is satisfied:

$$\left(\eta\alpha_Q^h(\eta)(\tilde{\theta}-\eta)(A_1(\eta)+A_2(\tilde{\theta},\eta))-A_1(\eta)A_2(\tilde{\theta},\eta)\alpha_Q^f(\eta)\tilde{\theta}\right)=0 \tag{49}$$

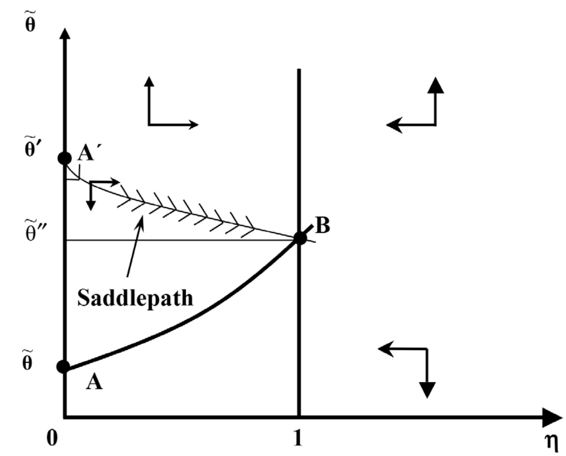
By totally differentiating equation (49), after rearranging I obtain $d\tilde{\theta}/d\eta < 0$.

Thus, $\dot{\theta}=0$ defines a downward-sloping curve in Figure 3. Starting from any point on this curve, an increase in η leads to $\dot{\tilde{\theta}} > 0$ and a decrease in η leads to $\dot{\tilde{\theta}} < 0$. The right-hand side of equation (1) is independent of $\tilde{\theta}$, and therefore the $\dot{\eta}=0$ locus is a vertical line. Starting from any point on this line, decrease in η leads to $\dot{\eta} > 0$. The area to the left of the vertical line (i.e., locus $\dot{\eta}=0$) identifies a region in which the potential number of adopters is greater than one. Therefore, this region is not feasible. There exists a downward-sloping saddlepath going through the balanced-growth equilibrium point B. Thus, I arrive at:

Proposition 3. *Assume that* $\partial\dot{\tilde{\theta}}/\partial\tilde{\theta} < \delta$. *Then, there exists a negative-sloping globally stable-saddle-path going through the final balanced-growth equilibrium point B. Along the saddle path, both the measure of industries that adopt the new GPT, η, and home's relative wage, ω, increase.*

The analysis is predicated on the assumption of perfect foresight.[23] When the new GPT arrives, the range of goods Home exports, $\tilde{\theta}$, jumps upward instantaneously to $\tilde{\theta}'$ (point A' in Figure 3). This jump increases Home's relative wage since there is more intense competition for workers at Home in order to produce more goods. The higher values of $\tilde{\theta}$ and ω lower the discounted expected monopoly profits at Home (see assumption (A.1) and equations (41)–(43)) and raise the discounted expected monopoly profits at Foreign. As a result, Foreign starts engaging in more R&D and gains back its competitiveness (in both R&D and production) in some of the industries that lost comparative advantage to Home. During the transition dynamics (i.e., as the equilibrium moves from point A' to point B in Figure 3), the range of goods Home exports, $\tilde{\theta}$, decreases, and the relative wage decreases to adjust the equilibrium in Home and Foreign labor markets. At point B in Figure 3, all industries at Home have adopted the new GPT.

FIGURE 3: Stability of the Balanced-Growth Equilibrium



Source: own elaboration.

Conclusions

This paper presented a simple and tractable framework of an open economy growth and trade model that incorporates the introduction and diffusion of a GPT. The previous literature on "quality-ladders" framework that analyzed Ricardian models of trade exhibits the scale effects-property. In order to be consistent with the empirical literature on the scale effects property, I have developed a model of trade based on "quality-ladders" growth without scale effects to analyze how GPTs affect the pattern of trade and how the relative wages are determined in steady-state equilibrium.

This model provides new insights and additional findings regarding the GPT-trade literature. In the presence of the new GPT, the model identifies a unique steady-state equilibrium, in which the pattern of trade in goods is determined by comparative advantage across industries. In addition and in contrast to earlier work, the model predicts that the pattern of trade is determined by additional factors such as population growth and the R&D difficulty parameter. Unlike in previous work, factor price equalization is not a property of the equilibrium and there is no trade in R&D services.

With the introduction of a new GPT in the Home country, there are two steady-state equilibria. The industries using the new GPT become more productive and thus make final goods producers in Home gain competitiveness. However, based on the transitional dynamics, the model shows that a negative-sloping globally stable-saddle-path exists. During the transitional dynamics, final goods producers in Foreign start engaging in more R&D and gain back their competitiveness (in both R&D and production) in some of the industries that lost its comparative advantage to Home.

The findings in this paper have important trade policy implications. One possible implication is that policymakers can affect the amount of R&D investment positively through various instruments such as research subsidies. When the global R&D investment increases, the probability that the incumbent firm in one country will be replaced by a follower firm from another country increases and thus the locus of production and the pattern of trade is affected. Alternatively, the government may decide to protect some industries in the high tech sector (due to spillover effects) by imposing tariffs. These industries will enjoy protection and the technological benefits associated with the new GPT will be enlarged. This is consistent with the infant industry argument of the international trade theory. Another possible policy implication of the results presented in this paper is that attempts to promote GPTs in a particular industry will affect positively the competitiveness in that industry and allow the country where the industry is affected to develop a comparative advantage.

The present model has also industrial policy implications. For example, are all firms within each industry ready to adopt the new GPT? Large firms have an advantage over small firms in adopting new technologies and affect positively the rate of GPT diffusion. An increase in the productivity gains generated by the new GPT makes the firm with the new GPT more productive and accelerates the adoption and diffusion of the new GPT. This in turn increases the economy-wide resources devoted to R&D.

Given the relative simplicity of the model, it can be extended in several fruitful directions. One could examine the GPT diffusion on a global scale. For example, the diffusion of the new GPT within an industry from one country to the other can occur with a time lag. It would be interesting to analyze the long-run and transitional dynamic effects of a new GPT on trade patterns. Another potential extension of the present model is the introduction of trade instruments and their effects on the pattern of trade between countries. Alternatively, a North-South model of trade might yield interesting implications.

Notes

[1] Iordanis Petsas, Department of Economics and Finance, Kania School of Management, University of Scranton; Author's e-mail address: iordanis.petsas@scranton.edu

[2] For example, Helpman and Trajtenberg [1998b] provide evidence for the diffusion of the transistor. They state that transistors were first adopted by the hearing aids industry. Later, transistors were used in radios followed by the computer industry. These three industries are known as early adapters of the transistor GPT. The fourth sector to adopt the transistor was the automobile industry, followed by the telecommunication sector.

[3] For example, Griliches [1957] studied the diffusion of hybrid seed corn in 31 states and 132 crop-reporting areas among farmers. His empirical model generates an *S*-curve diffusion path. Andersen [1999] confirmed the *S*-shaped growth path for the diffusion of entrepreneurial activity, using corporate and individual patents granted in the U.S. between 1890 and 1990. Jovanovic and Rousseau [2001] provide more evidence for an *S*-shaped curve diffusion process by matching the spread of electricity with that of personal computer use by consumers.

[4] At the aggregate level, information technology is identified with the output of computers, communications equipment, and software. These products appear in the GDP as investments by businesses, households, and governments along with net exports to the rest of the world.

[5] Another study from OECD documents that U.S. investment in information processing equipment and software increased from 29% in 1987 to 52% in 1999. The diffusion of information and communication equipment accelerated after 1995 as a new wave of information and communication equipment, based on applications such as the World Wide Web and the browser, spread rapidly throughout the economy.

[6] [5] Dinopoulos and Syropoulos [2001] have recently developed a two-country general equilibrium model of endogenous Schumpeterian (R&D based) growth without scale effects to examine the effect of globalization on economic growth when countries differ in population size and relative factor endowments.

[7] Devine [1983] provides an excellent historical perspective on electrification where he documents the transformation from shafts to wires. He states: "Until late in the nineteenth century, production machines were connected by a direct mechanical link to the power sources that drove them. In most factories, a single centrally located prime mover, such as a water wheel or steam engine, turned iron or steel "line shafts" via pulleys and leather belts…. By the early 1890 s then, direct current motors had become common in manufacturing, but were far from universal. Mechanical drive was first electrified in industries such as clothing and textile manufacturing and printing, where cleanliness, steady power and speed, and ease of control were critical". Helpman and Trajtenberg [1996] explore the adoption of the transistor, an important semiconductor GPT by a number of industries. As they state: The early user sectors were hearing aids and computers. The prominent laggards were telecommunications and automobiles. These examples indicate that the timing of adopting a new GPT differs across industries.

[8] See Thirtly and Ruttan [1987, pp. 77–89] for various applications of the epidemic model to the diffusion of technology.

[9] When, then $t \rightarrow -\infty$. If one ass $\eta = 0$ umes that the new GPT arrives at Home at time $t = 0$, then $\eta > 0$. That is, the new GPT arrives at Home by a given fraction of industries η (i.e., the industry or industries that developed this particular GPT).

[10] Barro and Sala-i-Martin [1995 Ch.2] provide more details on this formulation of the household's behavior within the context of the Ramsey model of growth.

[11] Taylor [1993] incorporates multinational corporations in a model of endogenous growth and trade. In his model, innovations are always implemented on front line production technologies (i.e, that is technologies that are minimum cost given the prevailing wage rates) and when innovation and implementation occur at different countries, the resulting transactions are considered as imports and exports of R&D.

[12] In proposition 1, I provide sufficient conditions under which this assumption holds.

[13] The empirical evidence on returns to scale of R&D expenditure is inconclusive. Segerstrom and Zolnierek [1999] among others developed a model where they allow for diminishing returns to R&D effort at the firm level and industry leaders have R&D cost advantages over follower firms. In their model, when there are diminishing returns to R&D and the government does not intervene both industry leaders and follower firms invest in R&D.

[14] Taylor [1993] has introduced heterogeneity in the research technologies and in the technological opportunity for improvements in technologies. The presence of heterogeneous research technologies makes trade in R&D services between countries possible. The absence of heterogeneous research technologies in the present model, makes the removal of scale effects more tractable, but eliminates the possibility of trade in R&D services between the two countries.

[15] The variable $I^i(\theta, t)$ is the intensity of the Poisson process that governs the arrivals of innovations in industry θ in country i. Dinopoulos and Syropoulos [2001] model the strategic interactions between a typical incumbent and its challengers as a differential game for Poisson jump processes and derive the equilibrium conditions that govern the solution to a typical R&D contest. They also provide an informal and intuitive derivation of these conditions. In the present model, I follow their informal derivation to derive my results.

[16] See Dinopoulos and Thompson [1999] for an overview of these models.

[17] Informational, organizational, marketing, and transportation costs can readily account for this difficulty. Arroyo, et al. [1995] have proposed this specification under the name of the *permanent effects of growth* (PEG) model, and have provided time-series evidence for its empirical relevance.

[18] Dinopoulos and Thompson [1998] provide micro foundations for this specification in the context of a model with horizontal and vertical product differentiation.

[19] If the monopolist is located in Home, the monopoly profits are define by equation (16) and if the monopolist is located in Foreign, the monopoly profits are defined by equation (17).

[20] In Appendix, I derive the mutual resource schedule and show that it is upward-sloping in (θ,ω) space.

[21] For sufficiently large $\bar{N}^f/\bar{N}^h$, the $MR(\tilde{\theta})$ schedule intersects the $RD(\tilde{\theta})$ schedule at a point above the 45° line, such as $\omega > 1$.

[22] See also Mulligan and Sala-i-Martin [1991] for more details on this method.

[23] There also exists a degenerate equilibrium where the adoption of the new GPT is not completed. Suppose that when a new GPT arrives, every potential producer expects that no one will produce more goods. As a result, it does not pay to increase production, because the new GPT will never be fully adopted. In this event, the pessimistic expectations are self-fulfilling, and no new GPTs are fully adopted. I do not discuss these types of equilibria in what follows.

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APPENDIX

A.1 Proof of Lemma 1

Lemma 1 results from equations (23) and (25) (after taking into account equations (16) and (17). Then, from the zero profit conditions, one can obtain the mutual R&D condition:

$$\omega = RD(\tilde{\theta}) = \frac{\alpha_Q^f(\tilde{\theta})}{\alpha_Q^h(\tilde{\theta})\gamma_\zeta} \tag{A.1}$$

The slope of the mutual R&D condition is downward sloping due to assumption (A.1) in the paper. There is an industry $\tilde{\theta} \in [0,1]$, where both countries, Home and Foreign, undertake R&D. For this industry, the zero profit conditions yield $V^f(\tilde{\theta}) = V^h(\tilde{\theta})$.

If in industry θ, R&D is undertaken by Home, then the zero profit conditions for R&D imply that Foreign has negative profits in this particular industry (see equations (23) and (25)). Since firms located in the Home country have higher discount profits than foreign firms for the goods in the range $\theta \in [0,\tilde{\theta})$, this prevents challengers from the Foreign country to finance their R&D costs in the range of industries $\theta \in [0,\tilde{\theta}]$ and thus choose not to engage in R&D (since this would yield negative profits). The reverse is true for those industries that Foreign undertakes R&D. Home has negative profits in the industries $\theta \in (\tilde{\theta},1]$, so it does not pay off to engage in R&D in those industries. Thus, both countries will develop and sustain their comparative advantage in the industries they conduct their R&D.

A.2 Proofs of Propositions 1, 2, and 3

A.2.1 Proposition 1

In order for Home's relative wage to be greater than one (assumption (14) in the main text), the mutual R&D schedule (given by equation (26) should lie above the $\omega = 1$ line.

The intersection of the R&D condition and mutual resource curves yield the unique steady-state equilibrium values of the marginal industry $\tilde{\theta}^*$ and the relative wage at home ω^*. From Lemma 1, it follows that home and foreign have sustained comparative advantages in R&D in the industries $[0,\tilde{\theta})$ and $(\tilde{\theta},1]$ respectively. Since international licensing and multinational corporations are ruled out, this will imply that each vertically differentiated good must be manufactured in the country in which the most recent product improvement has taken place. Thus, the home country conducts R&D, produces, and exports the state of the art product for each industry $\theta \in [0,\tilde{\theta}^*)$ while the foreign country conducts R&D, produces, and exports the state of the art product for each industry $\theta \in (\tilde{\theta}^*,1]$.

A.2.2 Proposition 2

I can write the two equilibrium relationships governing Figure 1 in a more general form as follows:

$$\omega \equiv RD(\tilde{\theta}, \gamma_{\varsigma}) \text{ , where } RD_1 < 0, RD_2 < 0, \tag{A.2}$$

$$\omega \equiv MR(\tilde{\theta}, \bar{N}^f, \bar{N}^h, k, \alpha_R\ \rho, g_N) \text{ , where } MR_1 > 0, MR_2 > 0, MR_3 < 0, \tag{A.3}$$

$$MR_4 < 0, MR_5 > 0, MR_6 > 0, MR_7 > 0.$$

I totally differentiate equations (26) and (40) in the main text and obtain the following system of two equations in the differentials of two endogenous variables as follows:

$$d\omega - RD_1 d\tilde{\theta} = RD_2 d\gamma_{\varsigma}$$

$$d\omega - MR_1 d\tilde{\theta} = MR_2 d\bar{N}^f + MR_3 d\bar{N}^h + MR_4 d\kappa + MR_5 d\alpha_R + MR_6 d\rho + MR_7 dg_N \tag{A.4}$$

I can write the system (A.4) in the reduced form as follows:

$$\begin{bmatrix} 1 - RD_1 \\ 1 - MR_1 \end{bmatrix} \begin{bmatrix} d\omega \\ d\tilde{\theta} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & RD_2 & 0 & 0 & 0 \\ MR_2 & MR_3 & MR_4 & 0 & MR_5 & MR_6 & MR_7 \end{bmatrix} \begin{bmatrix} d\bar{N}^f \\ d\bar{N}^h \\ d\kappa \\ d\gamma_{\varsigma} \\ d\alpha_R \\ d\rho \\ dg_N \end{bmatrix}, \tag{A.5}$$

I calculate the determinant of the matrix of the endogenous variables (which I denote with Δ) as follows:

$$\Delta = \begin{vmatrix} 1 & -RD_1 \\ 1 & -MR_1 \end{vmatrix} = RD_1 - MR_1 < 0. \tag{A.6}$$

Using the system of equations given by (A.5) and by employing the Cramer's rule, I establish the comparative steady-state results regarding. I calculate the determin ω ant of the matrix formed by replacing the second column of the matrix of the endogenous variables in (A.5) with the corresponding column vector of the exogenous variable in consideration. Thus, I obtain the following results:

$$\frac{d\omega}{d\bar{N}^f} = \frac{RD_1MR_2}{\Delta} > 0, \tag{A.7}$$

$$\frac{d\omega}{d\bar{N}^h} = \frac{RD_1MR_3}{\Delta} < 0, \tag{A.8}$$

$$\frac{d\omega}{d\kappa} = \frac{RD_1MR_4}{\Delta} < 0, \tag{A.9}$$

$$\frac{d\omega}{d\gamma_\zeta} = \frac{-MR_1RD_2}{\Delta} < 0, \tag{A.10}$$

$$\frac{d\omega}{d\alpha_R} = \frac{RD_1MR_5}{\Delta} > 0, \tag{A.11}$$

$$\frac{d\omega}{d\rho} = \frac{RD_1MR_6}{\Delta} > 0, \tag{A.12}$$

$$\frac{d\omega}{dg_N} = \frac{RD_1MR_7}{\Delta} < 0. \tag{A.13}$$

The signs of equations (A.7) through (A.13) prove Proposition 2.

Using the system of equations given by (A.5), I establish the comparative steady-state results regarding $\tilde{\theta}$. I calculate the determinant of the matrix formed by replacing the second column of the matrix of the endogenous variables in (A.5) with the corresponding column vector of the exogenous variable in consideration. Thus, I obtain the following results:

$$\frac{d\tilde{\theta}}{d\bar{N}^f} = \frac{MR_2}{\Delta} < 0, \tag{A.14}$$

$$\frac{d\tilde{\theta}}{d\bar{N}^h} = \frac{MR_3}{\Delta} > 0, \tag{A.15}$$

$$\frac{d\tilde{\theta}}{dk} = \frac{MR_4}{\Delta} > 0, \tag{A.16}$$

$$\frac{d\tilde{\theta}}{d\gamma_\zeta} = \frac{RD_2}{\Delta} > 0, \tag{A.17}$$

$$\frac{d\tilde{\theta}}{d\alpha_R} = \frac{MR_5}{\Delta} < 0 \tag{A.18}$$

$$\frac{d\tilde{\theta}}{d\rho} = \frac{MR_6}{\Delta} < 0, \tag{A.19}$$

$$\frac{d\tilde{\theta}}{dg_N} = -\frac{MR_7}{\Delta} > 0. \tag{A.20}$$

The signs of equations (A.14) through (A.20) prove Proposition 3.

A.2.3 Proposition 3

I analyze the transitional dynamics of the model by adapting the time-elimination method described by Mulligan and Sala-i-Martin [1992]. The time-elimination method enables one to construct a system of two differential equations that govern the evolution of $\tilde{\theta}$ and η.

In order to prove that exists a negative sloping globally saddle path, I use the time elimination method. The slope of the policy function can be obtained by taking the ratio of the two differential equations that govern the dynamic behavior of the system:

$$\frac{\partial\tilde{\theta}}{\partial\eta} = \tilde{\theta}'(\eta) = \frac{\dot{\tilde{\theta}}}{\dot{\eta}} = ,$$

$$\frac{\dfrac{\left(\eta\alpha_Q^h(\eta)(\tilde{\theta}-\eta)(A_1(\eta)+A_2(\tilde{\theta},\eta)) - A_1(\eta)A_2(\tilde{\theta},\eta)\alpha_Q^f(\eta)\tilde{\theta}\right)\alpha_Q^f(\tilde{\theta})\delta(1-\eta)}{\tilde{\theta}A_1(\eta)\alpha_Q^f(\eta)[\alpha_Q^h(\tilde{\theta})(\tilde{\theta}-\eta)-\alpha_Q^f(\tilde{\theta})A_2(\tilde{\theta},\eta)]}\tilde{\theta}}{\delta\eta-\delta\eta^2} \tag{A.21}$$

Time does not appear in the above equation. To solve this equation numerically, there must be one boundary condition: that is, one point ($(\tilde{\theta},\eta)$, that lies on the stable arm. Even though the initial pair, $[\tilde{\theta}(0),\eta(0)]$, is unknown, the policy function goes through the steady state ($(\hat{\tilde{\theta}},\hat{\eta})$.

The slope of the policy function at the steady state is $\tilde{\theta}'(\eta) = \frac{\dot{\tilde{\theta}}}{\dot{\eta}} = \frac{0}{0}$, which is indeterminate. Applying the L'Hôpital's rule to this slope and evaluating it at the steady state values, it can be shown that the slope of the stable arm is negative as long as the shift in the marginal industry is less than the GPT diffusion rate $\partial\dot{\tilde{\theta}}/\partial\tilde{\theta} < \delta$. Along the saddle path, both the measure of industries that adopt the new GPT, η, and home's relative wage, ω, increase.