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Innovation, Diffusion, and Trade: Theory and Measurement*

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Abstract

Growth and imports are correlated across countries. However, the underlying mechanisms remain poorly understood. I develop a general equilibrium model in which imports and growth are connected by technological innovation and international diffusion through trade. Fitting the model to data on innovation, productivity, and trade in varieties, I find that most of the correlation is explained by these two mechanisms. Moreover, adoption has been particularly important in developing countries, accounting for about 80% of their growth in the last decade. Finally, I carry out a counterfactual analysis to examine the connections between trade and growth.

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1 Introduction

In the last decade, some countries in Asia and Europe grew much faster than average. Many of these countries also increased significantly the variety of goods they imported. For instance, China and India had average growth rates of about 8%, as well as a growth in imported varieties that was 5 times higher than in the United States, Japan or Germany—countries that grew, on average, at a rate of 2%.[1]

Although the positive correlation between imports and growth is well established, the underlying mechanisms are not well understood. Theories regarding the effects of imports on growth go back at least to Romer (1987) and Rivera-Batiz and Romer (1991). However, empirical work has been limited in part by lack of data. More recently, disaggregated trade data have become available for many countries, yielding new stylized facts. In particular, it appears that much of the increase in trade-to-GDP ratio stems from the extensive margin (number of goods traded) rather than the intensive margin (how much of each good is traded). Broda, Greenfield, and Weinstein (2008) show that, for the average country, the extensive margin explains 80% of the increase in this ratio.[2] Therefore, understanding the relation between growth in GDP and growth in imports requires an emphasis on the extensive margin of trade.

I develop a general equilibrium model in which imports and growth are connected by technological innovation and international diffusion through trade. There are two channels of growth: the "embodied" channel and the "disembodied" channel. As in Greenwood, Hercowitz, and Krusell (1997), the "embodied" channel is associated with some form of capital accumulation while "disembodied" productivity reflects residual, neutral productivity. In my model, "embodied" productivity is driven by technology accumulation, which occurs through two processes.[3] First, in the spirit of the new growth theory, a country accumulates technology as domestic firms innovate by investing in R&D. Technology is embodied in new goods. Second, a country can accumulate technology as firms import goods that

[1]Santacreu (2006) finds that over 60% of Ireland's growth during 1994–2003 was driven by an increase in the variety of goods it imported from highly innovative OECD countries.

[2]Broda and Weinstein (2006) find that, for developing countries, the extensive margin explains almost all of productivity growth. Hummels and Klenow (2002) also perform this decomposition for exports and find that the extensive margin explains two thirds of the increase in trade.

[3]A large literature studies whether differences in growth rates are driven mainly by factor accumulation (capital, in particular) or by total factor productivity (TFP) differences (see Young (1991)). Easterly and Levine (2001) and Klenow and Rodriguez-Clare (2005) show that it is differences in TFP that drive differences in growth rates across countries. Even though capital accumulation has been important in several Asian economies, TFP growth affects the marginal return on capital and thus could explain why the rental rate of capital has been so high in these countries.

embody foreign technologies. The main difference between domestic and foreign sources of technology is that domestic innovations can immediately be sold in the domestic market. In contrast, importing a foreign innovation requires that firms in an adoption sector invest resources over time in order to adapt the good in which is embodied.[4] As a result, the international diffusion of innovations is slow and the speed is endogenous. In this setting, a country's equilibrium allocation of resources to innovation versus adoption depends on its level of development and other characteristics.

I analyze both the steady state and the transition dynamics of the model. As in models of innovation and international diffusion, all countries grow at the same rate in the steady state, yet barriers to technology adoption create persistent income differences.[5] More interestingly, countries grow at different rates during the transition. In developing countries, the cost of adoption tends to be lower than the cost of innovation. As a result, the equilibrium allocation of resources to adoption is higher, and catching up allows these countries to grow faster. As the economy develops, the cost difference between innovation and adoption decreases, so domestic innovation increases. It is not unreasonable to assume that innovation requires a higher level of technology than adoption. Because rich countries are technologically more advanced, they allocate more resources to innovation. This is consistent with the data: developing countries adopt and grow more, whereas rich countries innovate more.

The model is fitted to 37 countries grouped into five regions: Asia, Eastern Europe, Western Europe, Japan, and the United States. I use Bayesian techniques and data regarding innovation, productivity, and trade at the product level to estimate the parameters governing innovation and diffusion. I find that the "embodied" channel explains between two thirds and three fourths of the correlation between growth in imports and growth in GDP per capita duiring the last decade. Within this channel, adoption of foreign innovations through trade arises as an important source of productivity growth for developing countries, whereas domestic innovation has been the main source of growth for developed countries. In fact, more than 80% of embodied growth in Asia can be explained by foreign innovations, especially from the United States and Japan. These two countries are also the main sources of foreign technology for other regions.[6]

[4]Consistent with recent empirical findings by Comin and Hobijn (2004), diffusion is modeled as a slow process in which the speed of diffusion depends on the amount of resources invested by the adopters. Eaton and Kortum (1999) find that international diffusion is much slower than domestic diffusion; I make the extreme assumption that diffusion is instantaneous within a country.

[5]See Rodriguez-Clare and Klenow (1997) for a review.

[6]Cameron, Proudman, and Redding (2005) analyze a model for a panel of U.K. manufacturing industries, in which innovation and technology transfer are the main sources of productivity growth for countries lagging behind the technology frontier. The authors find that technology transfer through international trade is the

Finally, I use counterfactuals to examine the link between trade and growth by changing various exogenous parameters. A 50% permanent decrease in the costs of adoption in Asia increases steady-state world growth rates by 1%; in the transition, trade rises and Asia grows faster than average. A 50% permanent increase in the innovation productivity in Asia increases-steady state world growth rates by 3%. The higher Asian productivity increases the demand of imports from the rest of the world. Both changes induce a positive correlation between imports and growth.

This paper builds on several streams of literature. The first stream concerns endogenous growth in which technology is embodied in new goods, as in Romer (1987). To this embodied growth I add an exogenous TFP process which represents disembodied technology as in Greenwood, Hercowitz, and Krusell (1997).

Second, I follow Eaton and Kortum (1996, 1999) in positing innovation and international technology diffusion as the potential channels of embodied technological progress.[7] In my framework, however, diffusion occurs through the endogenous process of trade in varieties. That is, firms must undertake a costly investment in order to import a good. Incentives for the importer differ across sources of imports and depend on the value of adopting a new technology. I adapt the approach used both in Comin and Gertler (2006) and Comin, Gertler, and Santacreu (2009) to the setting of an open economy.[8]

The lack of direct measures of adoption have led to the use of indirect measures, such as trade in intermediate goods (Rivera-Batiz and Romer (1991); Eaton and Kortum (2001, 2002)) or international patenting (Eaton and Kortum (1996, 1999)).[9] Because the aim of this paper is to understand the connections between trade and growth, I use trade as an indirect measure of diffusion in a similar manner to that of Coe, Helpman, and Hoffmaister (1997). These authors find that, for developing countries, TFP is significantly related to the stock of R&D carried out by their trading partners. My model complements this literature by taking explicit account of the mechanisms connecting trade and growth.

This paper also relates to the literature on trade in varieties, as in Feenstra (1994), Broda and Weinstein (2006), Broda, Greenfield, and Weinstein (2008), and Goldberg, Khandelwal, Pavcnik, and Topalova (2009). I follow their methodology to compute the extensive margin

main driving source of growth for these countries and they report a positive and statistically significant effect of distance with respect to the frontier on productivity growth.

[7]See Keller (2004) for a survey of empirical studies in innovation and diffusion.

[8]Further empirical evidence showing that innovations are not transferred to other locations at a negligible cost can be found in Griliches (1957) and Teece (1977).

[9]Comin and Hobijn (2004) provide direct measures of adoption for a large sample of countries and a large sample period; however, they do not distinguish between technologies created in the country and those from abroad.

of trade, but I model explicitly the incentives of different agents in the economy to undertake either R&D or adoption.[10]

The paper proceeds as follows. Section 2 examines the data. Section 3 presents the model; the steady state and the dynamics are solved in Sections 4 and 5, respectively. Section 6 explains the estimation procedure and reports the results. Sections 7 through 9 contain the experiments, and Section 10 concludes.

2 A first look at the data

To motivate the model that I develop next, this section presents data on innovation, trade, and productivity for a sample of 37 countries, which I divide into three groups: innovative economies in Europe, Japan, and the United States, which grow and import at lower than average rates; less innovative countries in Europe and Asia, which grow and expand imports more than average; and less developed countries in Africa and Latin America, which innovate and import at low rates. The data are summarized in Appendix A.

The positive relation between trade and growth is a well-established stylized fact. In the last decade, some countries in Asia and Europe have experienced a significant increase in their variety of imports and have been growing faster than average.[11] Figure 1 shows, for a 37-country sample, a positive correlation between the average growth rate of income per capita and the expansion in import variety.[12] The United States, Japan, and Germany are at one extreme, with lower import and productivity growth, whereas China, Vietnam, and India are at the other extreme. Even though the link between the two variables is clear from the graph, we cannot infer any causality and so the mechanisms that connect trade and growth remain an open question.

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[10] A variety is defined as a 6-digit category product from a particular source-country. This is the Armington assumption, by which countries specialize exogenously in producing a different good.

[11] One could argue that looking at exports is just as important as looking at imports to explain the development experienced by Asia and Eastern Europe. However, the correlation computed between productivity growth and growth in exported varieties is only 0.4, whereas the correlation is almost 0.8 between productivity growth and growth in imports.

[12] The average is taken over the period 1994–2003 for a sample of 37 countries. The red circles represent less developed countries in Asia, Europe, Africa, and Latin America; the blue circles represent rich countries in Europe, Japan, and the United States. I use bilateral trade data at the 6-digit level of disaggregation, from UN COMTRADE. A variety is defined as a 6-digit product from a specific source of exports. Growth in imported varieties is computed as in Broda, Greenfield, and Weinstein (2008), who adjust for quality and symmetry bias. Output growth is growth in real GDP per capita, from the Penn World Table, adjusted by the extensive margin of intermediate imports as in Feenstra (1994) and Broda, Greenfield, and Weinstein (2008).

Another feature of fast-growing countries is a relatively low level of income per capita, which signals a catching-up effect. Figure 2 plots the average growth rate of income per capita for the period 1994–2003 against the initial level in 1994. Once we eliminate Africa and Latin America, there is a clear positive correlation between the two variables. Thus, catching up is a feature of only those economies expanding the variety of goods that they import.[13]

Developing countries have a lower extensive margin of trade. In fact, there is a positive correlation between levels of income per capita and the level of imports across countries (see figure 3). Under the assumption that technology diffuses via international trade, this evidence suggests that rich countries have a higher level of foreign embodied technology whereas while less developed countries are increasing that level faster. To be consistent with the data, a model must allow for rich countries being technologically more advanced.

International diffusion via trade is a slow process. Using bilateral trade data from UN COMTRADE, I compute the hazard of adoption over the period 1994–2003 for the 37-country sample, which is grouped into five regions: Asia, Eastern Europe, Western Europe, Japan, and the United States.[14] The results are displayed in Table 1. The inverse of the hazard rate represents the average time that it takes, for each importer, to adopt goods from each exporter. On average, it takes between three and ten years to start importing a new good.[15]

Note that if diffusion were instantaneous, then all countries would have access to the same technology and so the levels of income per capita would be the same. At the other extreme, if there were no international diffusion then a country's growth rate would depend exclusively on technology accumulation through domestic innovation. Because rich countries invest more in doing R&D, we would expect them to grow at higher rates. Empirically, however, there is no a positive correlation between innovation and growth, when developing countries are added to the analysis. Figure 3 plots each country's R&D intensity against its growth in imported varieties. The correlation is negative, suggesting that less innovative countries are

[13]Even though Africa and Latin America begin with relatively low levels of GDP per capita, their expansion of imports and economic growth is low.

[14]Keller (2004) considered the importance of analyzing the interaction between these regions when he stated: "Many economists believe that the increased economic integration . . . has tended to increase the long-run rate of economic growth. If they were asked to make a prediction, they would suggest that prospects for growth would be permanently diminished if a barrier were erected that impeded the flow of all goods, ideas and people between **Asia, Europe and North America**."

[15]In Appendix E, I explain how the hazard of adoption is obtained using tools of survival analysis (or duration analysis) with censored data.

expanding imports faster and (see figure 1) growing more rapidly.[16] As described in the development literature, rich countries produce more goods and therefore have a higher level of domestic embodied technology.

3 The model

In this section, I construct an endogenous growth model of trade in varieties that captures the main features of the data. The economy is composed of M countries that interact with each other through trade. Technology is embodied in new goods that are used in final production. There are two channels of growth: embodied and disembodied. Innovation and adoption of new intermediate products are the source of embodied productivity growth; exogenous TFP shocks represent disembodied technological progress as in Greenwood, Hercowitz, and Krusell (1997).[17] Without loss of generality, I assume that there is not an exogenous death probability of products.[18]

Throughout the paper, whenever a variable has both a subscript and a superscript, the superscript indexes the destination of imports and the subscript indexes the source of exports. The goods are indexed by j and the time is indexed by t.

3.1 Preferences

In each country there is a representative consumer that supplies labor inelastically and, solves the following maximization problem

$$\max U(C_{it}) = \sum_{t=0}^{\infty} \beta^t C_{it}$$

$$\text{s.t.} \quad \sum \beta^t C_{it} = \sum \frac{Y_{it}}{(R)^t},$$

where β is the discount factor, C_{it} is consumption in country i at time t, R is the risk-free interest rate, and Y_{it} is final output. Note that consumers are risk neutral because they face a linear utility function on consumption.

[16] R&D intensity is measured as the fraction of workers that is allocated to research and development (data from the World Development Indicators in the World Bank).

[17] Other authors who study the role of trade in explaining growth-rate differences have focused on capital accumulation as the source of economic growth; see Ventura (1997).

[18] The data show that the rate at which products drop out of the sample is about 1%. The results would remain the same if the exogenous death probability were added.

From t[redacted] the risk-free [redacted]

3.2 Final producti[redacted]

At time t, each country i uses tra[redacted] Y_{it} according to the constant elastic[redacted]

$$Y_{it} = e^{\bar{g}a_{it}} \left(\sum_{n=1}^{M} \sum_{j=1} \right.$$ [redacted]

where M is the number of countries from which c[redacted] $\sigma > 1$ is the elasticity of substitution among differenti[redacted] amount of input j that is used in the production of final outp[redacted] for variety j.[20] The term A^{i}_{nt} is the total number of varieties [redacted] in country i from country n at time t; it is a measure of embodied[redacted] both domestic and foreign adopted intermediate goods. Finally, a_{it} cap[redacted] manufacturing productivity, or disembodied techn[illegible]ogy, which is assum[redacted] across sectors and to follow a first-order autoregressive process

$$a_{it} = \rho a_{i,t-1}$$ [redacted]

where $X_{it} = \omega_{it} L_{it}$ is total spending by country i, ω_{it} is wages, and P_{it} is the price index

$$P_{it} = \left(\sum_{n=i}^{M} \sum_{j}^{A^i_{nt}} c^i_{ntj} \left(p^i_{ntj}\right)^{1-\sigma} \right)^{\frac{1}{1-\sigma}}.$$

Here A^i_{nt} is the number of intermediate goods from country n that have been adopted by country i at time t, $c^i_{ntj} = (b^i_{ntj})^{\sigma}$, and $\frac{1}{A^i_{nt}} \sum_j c^i_{ntj} = c^i_{nt}$.[22]

3.3 Intermediate production sector

In the intermediate goods sector, there is a continuum of monopolistic competitive firms, each one of each selling a different variety to the competitive final good producer. Intermediate goods are produced according to the same CRS production function

$$x_{ijt} = l_{ijt}, \tag{3}$$

where $\sum_j l_{ijt} = L_{it}$ for l_{ijt} the amount of labor that each firm j employs to produce in country i, and L_{it} the total supply of labor in the country.[23]

These assumptions have implications for pricing, firm profits, and the value of having an innovation adopted in a country. Under monopolistic competition, each good is produced by a separate monopolist. Markets are segmented so that producers can set a different price in each market. Producers in each country endogenously choose to produce a different set of goods.[24]

Taking the demand by the final producers as given by equation (2), each intermediate-good firm chooses a price, p^i_{ntj} that is a constant mark-up over its marginal cost. Trade is assumed to be costly: there is an "iceberg" transport cost for products shipped from country n to i

[22] Observe that c^i_{ntj} is the expenditure share in variety j from country n by country i. In fact, $x^i_{nt} = \sum_j x^i_{ntj} = \sum_j \exp\left(\bar{g} a_{it}\right)^{\sigma} c^i_{ntj} X_{it} \left(\frac{p^i_{ntj}}{P_{it}}\right)^{(-\sigma)}$; however since, as I show later, $p^i_{ntj} = p^i_{nt}$ for all j, it follows that $x^i_{nt} = \exp(\bar{g} a_{it})^{\sigma} X_{it} \left(\frac{p^i_{nt}}{P_{it}}\right)^{(-\sigma)} \sum_j c^i_{ntj}$ and so $\frac{x^i_{ntj}}{x^i_{nt}} = \frac{c^i_{ntj}}{\sum_j c^i_{ntj}} = \frac{1}{A^i_{nt}}$. Therefore, $c^i_{ntj} = c^i_{nt}$ for all j. The fraction that each country spends in each good is the same across goods, but each country spends a different amount on each source n.

[23] Labor is the only factor of production in the economy, and it is assumed to be immobile across countries and perfectly mobile across sectors within a country. Labor is used for manufacturing of intermediate goods, innovation, and adoption.

[24] Although the Armington assumption of goods differentiated by source of exports implies that countries exogenously specialize in a different set of goods, in the setting of monopolistic competition the firms will produce differentiated goods.

that is equal to $d^i_n > 1$, with $d^i_i = 1$. Intermediate firms' prices differ in the domestic and the foreign market by the transport cost d^i_n. In other words, they set a price

$$p^i_{itj} = \bar{m}\omega_{it} \tag{4}$$

in the domestic market and

$$p^n_{itj} = \bar{m}(\omega_{it} d^n_i) \tag{5}$$

in each foreign market, where $\bar{m} = \frac{\sigma-1}{\sigma}$ is the constant markup. Note that the price set by intermediate goods is the same for every good and depends only on the exporter's wage and the iceberg transport costs.

Instantaneous profits by intermediate firms are given by

$$\pi^i_{ntj} = \left(\frac{1}{\sigma}\right) e^{\bar{g}a_{it}} (b^i_{ntj})^{\sigma} \left(\frac{p^i_{ntj}}{P_{it}}\right)^{-(\sigma-1)} \omega_{it} L_i;$$

they depend on the expenditure on each intermediate good, which is a function of wages ω_{it} and on the size L_{it} of the country. Larger countries thus constitute a bigger source of profits.

3.4 Innovation and adoption

In the model, connections between trade in varieties and growth are underpinned by the mechanisms of innovation and adoption. This section explains the mechanisms by which new goods are developed in an economy and how they diffuse to other countries. Both processes are endogenous and depend on the decisions of economic agents who seek to maximize profits.

Before explaining in detail the processes of domestic innovation and foreign adoption, let me introduce some notation. The term Z_{it} is the stock of technologies that have been developed in country i and are available to be adopted at time t; it represents the theoretical level of technology, which is the level of technology that would prevail in a country if diffusion were instantaneous. The term A^i_{nt} is the stock of foreign technologies that country i has successfully adopted from country n; it represents the actual level of technology in a country. Note that technologies enter the final production process, and hence are productive, only after they have been adopted.

Instantaneous diffusion within a country implies that, at each moment in time, the theoretical and actual number of technologies in a country is the same. That is, for country i,

$$A^i_{it} = Z_{it}.$$

Slow diffusion across countries implies that, at each moment in time, the actual level technology is a subset of the potential technology:

$$A^i_{nt} \leq Z_{nt}.$$

The effective level of technology in a country consists of both domestic and foreign technologies. For country i,

$$T_{it} = A^i_{it} + \sum_{n \neq i} A^i_{nt}$$

3.4.1 Innovation process

In a given country, new goods are introduced endogenously by a monopolist who allocates labor to R&D. As in Phelps (1964), the arrival of new goods at date t in location i, $Z_{i,t+1} - Z_{it}$, is determined by the fraction of workers that is allocated to research and by how productive the economy is at doing research:

$$Z_{i,t+1} - Z_{it} = \alpha^R_i T_{it} \left(\frac{R_{it}}{L_{it}} \right)^{\gamma_r} L_{it}; \tag{6}$$

here $\frac{R_{it}}{L_{it}}$ represents research intensity, with R_{it} the number of researchers and L_{it} the total number of workers, and $\alpha^R_i T_{it}$ represents the productivity of research.

The microfoundations of this function are as follows. In country i, workers are ranked according to their productivity at doing research. A worker with productivity j produces ideas at the stochastic rate $\alpha^R_i T_{it} \gamma_r \left(\frac{j}{L_{it}} \right)^{\gamma_{r-1}}$, where $\gamma_r \in (0, 1)$ is a parameter reflecting the extent of diminishing returns to allocating a larger share of workers to research.[25]

Research productivity, $\alpha^R_i T_{it}$, depends on two elements. The first is a country-specific parameter, α^R_i, that is identified by economic policies or institutions promoting innovation.[26] The second element is a spillover effect given by the effective number of technologies in the

[25] This assumption implies that a worker's talent as a researcher is drawn from a Pareto distribution. Workers in a country are equally productive at making intermediates but differ in their talent for research. They are assumed to be compensated in proportion to their marginal productivities. Thus, those who are more productive at doing research will become researchers. Nonetheless, we correct for population because, for the same research intensity, larger countries have a greater population from which to draw.

[26] Reasons for differences in the productivity parameter across countries may include better infrastructure and/or education.

country, T_{it}. Countries learn on the basis of the total number of goods that are available for final production. In this respect, there is learning by doing (domestically produced goods) and learning by using (imports). This assumption implies that countries with a higher extensive margin, which has been shown to be the case for rich countries, have a lower cost of innovation. Thus, ceteris paribus, richer countries invest a larger amount of resources in R&D. This specification is consistent with Grossman and Helpman (1991) and Romer (1994), and also with the data.

Another implication of the international spillovers component is that countries expanding their variety of foreign intermediate goods through imports are becoming better innovators, thereby increasing the number of goods that they produce and export. That is, even non-innovative countries can learn from importing intermediate goods. This reasoning is in line with the findings of Hallward-Driemeier (2000). Using data from five Asian countries, she observes that—prior to entry into export markets—productivity gains are associated with higher imports.

Finally, the spillover effect may lead rapidly adopting countries to shift from being mainly adopters to mainly innovators. Acemoglu, Aghion, and Zilibotti (2002) consider this process as a shift from an "investment-growth strategy" (adoption) to an "innovation-shift strategy" (innovation).

Subsequent to the innovation of a new technology, a competitive set of entrepreneurs bid for the right to produce the good. They pay the market price for an innovation, a price that is given by the discounted present value of profits that the entrepreneur who gets the production right expects to obtain from selling the good. Positive profits arise because the producers of the intermediate goods are monopolistic competitors, and they set prices while taking as given the demand by final producers in each potential market. In this sense, there is a fixed cost to start producing the good; this cost is given by the investment needed to acquire the technology from the research sector. Once a firm acquires the right to use the technology, it starts producing the intermediate good. Observe that the monopolist fully captures the profits arising from the innovation.

3.4.2 Technology diffusion

Intermediate goods that are invented and produced in a country must be adopted in order to be used by the final producers. In the model, diffusion within a country is instantaneous and costless, but across countries diffusion takes time. That is, when a new technology is produced in a country, it is immediately ready to be sold to the final sector in that

country.[27] This is not an unreasonable assumption. Eaton and Kortum (1996) estimate that the probability of diffusion within a sample of five innovative OECD countries is very high: between 0.8 and 0.9. However, in order to use a foreign good, adopters must first make a costly investment in each potential destination.[28] Whether or not adoption is successful is a random draw with positive probability, ε^i_{nt}. Note that the variable c^i_{nt} in equation (1) accounts for some markets n being more profitable than others. I assume that the value of this variable is realized only after the adopter decides to invest resources in adopting the good. That way, even goods with a low c^i_{nt} will be introduced to the market.

The probability of any idea from n diffusing to i can be expressed as

$$\varepsilon^i_{nt} = \alpha^A_i \frac{A^i_{nt}}{Z_{n,t+1}} \left(\frac{H^i_{nt}}{L_{it}} \right)^{\gamma_a} L_{it}. \tag{7}$$

Here H^i_{nt} denotes the amount of labor that adopters hire in country i to learn to use the product; α^A_i is a country-specific parameter that reflects barriers to adopting a new technology (a higher value of this parameter implies fewer barriers to adoption); and γ_a is the elasticity of adoption with respect to effort, which is assumed to be common across countries.[29] The latter term is a measure of how an increase in investment in adoption translates into an increase in the probability of importing a foreign good. Finally, $\frac{A^i_{nt}}{Z_{n,t+1}}$ represents the fraction of technologies that country i has already adopted from country n.[30]

Finally, I describe the process by which foreign technologies are introduced into a country via imports. As in Nelson and Phelps (1966) and Benhabib and Spiegel (1994), the rate at which the potential level of technology in country n is realized in actual technology in country i depends on the probability of adoption, ε^i_{nt}, and the stock of technologies from country n that country i has not yet adopted, $Z_{n,t+1} - A^i_{nt}$. This technological gap explains

[27] As shown in Section 2, the diffusion lag in the analized sample ranges between three and ten years.

[28] There is a fixed cost of adoption. The key assumption is that the cost is measured in terms of labor from the destination country. Other than that, the results are the same whether it is the exporter who hires the labor from the destination (fixed cost of exports) or it is the importer who incurs this cost (fixed costs of imports).

[29] Examples of economic policies that affect this parameter are an increase in investment in education, an improvement in telecommunication infrastructure that facilitates communication across countries, and trade policies. Eaton and Kortum (1996) and Benhabib and Spiegel (1994) analyze the dependence of the probability of adoption on different factors, including human capital. They find that human capital has a positive and significant impact on the likelihood of adoption.

[30] Think of this term as a measure of "remoteness". As the destination starts importing goods and becomes familiar with the exporter's products, the investment needed to start selling the good abroad is reduced. Interaction among the countries allows the importer to learn about the source; this leads, ceteris paribus, to an increase in the probability of adoption.

the dynamics of imports of new technologies as embodied in intermediate goods:[31]

$$A^i_{n,t+1} - A^i_{nt} = \varepsilon^i_{nt}(Z_{n,t+1} - A^i_{nt}). \tag{8}$$

Equation (8) implies that those goods invented in n that have not yet been imported by country i contribute to an expansion in the variety of exports to country i at a rate ε^i_{nt}.[32]

By solving equation (8) forward, the variety of imports is endogenously determined by the research effort undertaken throughout the world:

$$A^i_{nt} = \sum_{j=1}^{t} \varepsilon^i_{n,t-j} \prod_{k=1}^{j} (1 - \varepsilon^i_{n,t-k}) Z_{n,t-j+1}. \tag{9}$$

This equation shows that the dynamics of imports are determined by innovation around the world, as proxied by the theoretical level of technology.

In order to get a better understanding of the adoption mechanism, I substitute equation (7) into the law of motion for new imports, equation (8), and obtain

$$A^i_{n,t+1} - A^i_{nt} = \alpha^A_i \left(\frac{H^i_{nt}}{L_i}\right)^{\gamma_a} L_i \frac{A^i_{nt}}{Z_{n,t+1}} (Z_{n,t+1} - A^i_{nt}). \tag{10}$$

Rearranging, then yields

$$A^i_{n,t+1} - A^i_{nt} = \alpha^A_i \underbrace{\left(\frac{H^i_{nt}}{L_i}\right)^{\gamma_a}}_{\text{Investment in adoption}} L_i \underbrace{A^i_{nt}}_{\text{International spillover}} \underbrace{\left(1 - \frac{A^i_{nt}}{Z_{n,t+1}}\right)}_{\text{Relative backwardness}} . \tag{11}$$

The number of new goods that country i imports (adopts) from country n at time t depends on three components: (i) investment in adoption, (ii) the number of goods that country i has already imported from country n up to time t; and (iii) relative backwardness. This third component is a factor because, for countries that are farther away from the exporter's technological frontier (lower $\frac{A^i_{nt}}{Z_{n,t+1}}$), an increase in the number of imports will have a greater impact on growth rates. Empirically, countries that are expanding their range of imports rapidly are relatively backward countries that are also experiencing higher than average growth rates.

[31] Cummins and Violante (2002) focus on the adjustment of productivity growth to technological innovations. They calculate that the gap between average productivity and the productivity of the best technology rose from 15% in 1975 to 40% in 2000. This finding is consistent with technology diffusion models that claim learning about new technologies can generate long implementation lags because resources are channeled into the process of adapting current production structures to to accommodate the new technology.

[32] If diffusion were instantaneous, then $\varepsilon^i_{nt} = 1$ and, by equation (8), $A^i_{nt} = Z_{nt}$ for all t. If, on the contrary, there were no investment in adoption then $\varepsilon^i_{nt} = 0$ and, by equation (8), $A^i_{n,t+1} = A^i_{nt}$ for all t.

Notice that this factor arises from the product of two other terms: $\frac{1}{Z_{n,t+1}}\left(Z_{n,t+1}-A^i_{nt}\right)$.[33] The first term implies that, as country n's technology becomes more advanced, country i needs to invest more resources to adopt a given number of goods from n; the second term reflects that, when a country's imports are low relative to the technology frontier of the source, every successful technology adoption implies an expansion in the number of imports.[34]

3.4.3 The value of an idea

In the model economy, there are two profit maximization decisions: how much labor to invest in R&D and how much labor to invest in adoption. The decisions are based on the value of inventing and adopting a new technology.

The owner of a technology can earn profits only after the good has been adopted. There is instantaneous diffusion within a country, so the value W^i_{it} of a new good that is used domestically, is the present discounted value of future domestic profits:

$$W^i_{it} = \pi^i_{it} + \beta W^i_{i,t+1}, \tag{12}$$

where β is the discount factor, π^i_{it} are domestic profits for a firm in country i at time t, and $W^i_{i,t+1}$ is the continuation value.

Slow diffusion across countries implies that a technology invented in country n at time t will be adopted by country i at $t+1$ with probability ε^i_{nt}. The value of an idea invented in n at time t that has not yet been adopted by i is

$$J^i_{nt} = \max_{H^i_{nt}}\{-H^i_{nt}\omega_{it} + \beta\varepsilon^i_{nt}(H^i_{nt})W^i_{n,t+1} + \beta(1-\varepsilon^i_{nt}(H^i_{nt}))J^i_{n,t+1}\}.$$

At time t, firms invest H^i_{nt} units of labor to adopt the good. There is a fixed cost of adoption, given by $-H^i_{nt}\omega_{it}$. At time $t+1$, with probability ε^i_{nt} the country is successful and obtains profits forever. With probability $(1-\varepsilon^i_{nt})$, this technology will not be adopted though the

[33] As in Howitt (2000).

[34] Equation (11) can be expressed in terms of growth rates as

$$g_{in,t} = \alpha^A_i \left(\frac{H^i_{nt}}{L_i}\right)^{\gamma_a} L_i(1-\tau^i_{nt}),$$

where $\tau^i_{nt} = \frac{A^i_{nt}}{Z_{n,t+1}}$.

country may invest resources to adopt the good in the future. The value of a technology from n that has been adopted by i at time t is

$$W_{nt}^{i} = \pi_{nt}^{i} + \beta W_{n,t+1}^{i}.$$

In this specification, J_{nt}^{i} is the price that adopters in country i are willing to pay to intermediate firms in country n to buy their products and sell them in country i. It is also the profit received by intermediate producers in the source country.

Finally, V_{it} is the market price of an innovation. This price is given by the value of selling the good in the domestic market and the expected value of selling the good in each of the foreign markets: $V_{it} = \sum_{n=1}^{M} J_{nt}^{i}$ with $J_{it}^{i} = W_{it}^{i}$.

It is important to note that there are two trade costs in the model. One is the "iceberg" transport cost, which determines (once the good is traded) how much of the intermediate good is shipped across countries. The other one is a fixed cost, and affects whether or not a new product is imported: this cost is determined by barriers to technology adoption, as explained in Section 3.4.2.

3.4.4 Optimal investment in innovation

Innovators choose the amount of labor that maximizes profits. Taking as given the market price V_{it} of an innovation, they solve the maximization problem

$$\max_{R_{it}} V_{it}(Z_{i,t+1} - Z_{it}) - \omega_{it} R_{it}$$

$$\text{s.t.} \qquad Z_{i,t+1} - Z_{it} = \alpha_i^R T_{it} \left(\frac{R_{it}}{L_{it}} \right)^{\gamma_r} L_{it}.$$

Country i invests in R&D up to the point where the marginal benefit of research is equal to the marginal cost, which is given by the wage ω_{it}. Thus,

$$\gamma_r \alpha_i^R T_{it} \left(\frac{R_{it}}{L_{it}} \right)^{\gamma_r - 1} V_{it} = \omega_{it}. \tag{13}$$

The marginal benefit of performing research depends on its productivity $\gamma_r \alpha_i^R T_{it} \left(\frac{R_{it}}{L_{it}} \right)^{\gamma_r - 1}$

and on the market price V_{it} of an innovation.

3.4.5 Optimal investment in adoption

Intermediate producers in country n hire H_{nt}^i units of labor in country i in order to maximize the profits J_{nt}^i from selling the good in that country. These producers solve the following problem

$$\max_{H_{nt}^i} J_{nt}^i = -H_{nt}^i \omega_{it} + \beta \varepsilon_{nt}^i W_{n,t+1}^i + \beta(1-\varepsilon_{nt}^i) J_{n,t+1}^i$$

$$\text{s.t.} \qquad \varepsilon_{nt}^i = \alpha_i^A \left(\frac{H_{nt}^i}{L_{it}}\right)^{\gamma_a} L_{it} \frac{A_{nt}^i}{Z_{n,t+1}}.$$

Intermediate producers in n hire labor in i up to the point where the marginal benefit equals the marginal cost:

$$\gamma_a \alpha_i^A \left(\frac{H_{nt}^i}{L_{it}}\right)^{\gamma_a - 1} \frac{A_{nt}^i}{Z_{n,t+1}} (W_{n,t+1}^i - J_{n,t+1}^i) = \omega_{it}. \tag{14}$$

Notice that the marginal benefit depends positively on the (i) productivity of adoption,

$$\gamma_a \alpha_i^A \left(\frac{H_{nt}^i}{L_{it}}\right)^{\gamma_a - 1} \frac{A_{nt}^i}{Z_{n,t+1}},$$

,

and (ii) the difference between what producers can earn if adoption is successful, W_{nt}^i, and the value of a nonadopted intermediate good, J_{nt}^i.

It is important to note that the relevant decision is not *whether* to adopt a new technology but rather *when* to adopt it. The optimal action ultimately depends on expected future profits.

3.5 The labor market

Labor is the only factor of production in this economy, and it is used for manufacturing, innovation, and adoption. Equilibrium in the labor market implies that

$$L_{it} = L_{it}^M + L_{it}^R + L_{it}^A, \tag{15}$$

where L_{it}^M is the amount of labor employed in manufacturing, $L_{it}^R = R_{it}$ is the amount of labor used by the innovators, and $L_{it}^A = \sum_{n=1}^M H_{nt}^i$ is the amount of labor demanded by the adopters. In equilibrium, the sum of these three terms must equal L_{it}, the total labor force.

3.6 Labor market–clearing condition

Balanced trade and the assumption that labor is the only factor of production in the economy imply that we can close the model with the labor market clearing condition. In other words, the amount of labor used in production must equal the total amount of labor available in the economy:

$$\sum_{i=1}^M A_{nt}^i x_{nt}^i = \bar{m}\omega_{nt} L_{nt}^M. \tag{16}$$

The LHS of equation (16) represents total expenditure in manufactures from country n by each country i; the RHS is the value of total supply of labor from country n. This condition determines the equilibrium relative wage. Observe that, in the model, relative wages also reflect relative income per capita.

3.7 The equilibrium

For all i 2Tf176.5150Td(L)3.52391TJR1427.97011Tf7.98(i)2.7624TJR5811.955eR581449552Tf8.520Td(2(.

- Given prices and initial conditions, R_{it} solves the innovator's problem (equation (13)).
- Given prices and initial conditions, $\{H^i_{nt}, \pi^i_{nt}, W^i_{nt}, J^i_{nt}\}$ solves the adopter's problem (equation (14)).
- The laws of motion for A^i_{nt} and Z_{nt}, given by equations (6) and (8), are satisfied.
- Feasibility is satisfied by equation (1).
- Prices are such that the labor market clears.

4 Balanced growth equilibrium

In this section I solve for the balanced growth equilibrium of the economy. In steady state, all endogenous variables grow at a constant rate. Population is also assumed to be constant. Therefore, by equation (15), the allocation of labor to manufacturing, adoption, and research is also constant.

Technology diffusion and catching up assure that all countries eventually grow at the same rate. Countries differ in their relative levels of technology, as a function of the country-specific parameters: L_i, d^i_n, α^R_i, and α^A_i.[35]

Equation (6) implies that the number of domestically created varieties grows at the same rate as the total number of goods available in the final production sector. Similarly, from equations (8) and (7) it follows that the number of adopted domestically produced varieties grows at the same rate, which translates into a constant probability of adoption.

In steady state, the growth rates are the same across countries. To see this,

$$g_i = \frac{\Delta T_i}{T_i} = \frac{\Delta Z_i}{T_i} + \sum_{n=1}^{M} \frac{\Delta A^i_n}{T_i}. \tag{17}$$

If equations (6) and ((8)) are substituted into equation (17), then productivity growth in steady state can be expressed as a function of the amount of research that has been done around the world:

$$g = g_i = \alpha_i r_i^{\gamma_r} + \sum_{n=1}^{M} \varepsilon^i_n \sum_{s=1}^{t} (1-\varepsilon^i_n)^{-(t-s)} \alpha_{ns} r_{ns}^{\gamma_r} \frac{T_{ns}}{T_{it}}. \tag{18}$$

[35] Jovanovic (2009) develops a model in which diffusion lags depend on income differences. In my model, differences in the rate of adoption determine dispersion in income per capita across countries.

In steady state, $T_{ns} = T_{nt}(1+g)^{(t-s)}$ and $r_{ns} = r_n$ for all s; hence, given that instantaneous diffusion within the country implies that $\varepsilon_{ii} = 1$, equation (17) can be rewritten as

$$g = \sum_{n=1}^{M} \varepsilon_{in} \alpha_n r_n^{\gamma_r} \sum_{s=1}^{M} \left(\frac{(1-\varepsilon_n^i)}{(1+g)} \right)^{-(t-s)} = \sum_{n=1}^{M} \varepsilon_n^i \alpha_n r_n^{\gamma_r} \frac{(1+g)}{g+\varepsilon_n^i} \frac{T_{nt}}{T_{it}}. \tag{19}$$

With positive values for γ_r, α_n, ε_{in}, and $r_n = \frac{R_n}{L_n}$, the Frobenius theorem guarantees that we can obtain a value for the growth rate g and for relative productivities $\frac{T_i}{T_n}$. A key feature of the equilibrium is that the growth rate in steady state depends on the investment in world R&D. There are two components of growth: domestic and foreign sources of R&D (equation (19)).

It is important to note that, if there were no sources of heterogeneity in the world (i.e., if $\alpha_i^R = \alpha^R$, $\alpha_i^A = \alpha^A$, $L_i = L$, and $d_n^i = d$ for all i and n), then eventually a steady-state equilibrium would prevail: all the countries investing the same amount of labor into R&D and adoption, demanding the same amount of intermediate goods, and reaching the same level of income per capita.

5 Transitional dynamics

Differences in growth rates across countries arise in the transition and depend on differences in investment in innovation and adoption, which ultimately depend on differences in development. For countries in early stages of development, it is cheaper to adopt than to innovate; hence, such countries invest more resources in adopting foreign goods. Catching up then allows them to grow more rapidly than average. As they start importing more goods, the productivity of doing research increases via the spillover effect, and this reduces the gap between the costs of innovation and adoption. As a result, these countries start reallocating more resources into innovation.

In sum, countries located in different points on the transition path invest and adopt at different rates and therefore grow at different rates. Rich countries are mainly innovators, and less developed countries are mainly adopters of foreign innovations.

6 Empirical strategy

6.1 Bayesian estimation

I estimate the model using Bayesian techniques. The methodology is described in Schorfheide (1999). The Dynare program (see (Juillard 1996)) is used to solve and estimate the model.[36]

6.2 Data and priors

To make the model more tractable, I group the sample of 37 countries into five regions such that countries in the same region share common characteristics (similar innovation intensity, extensive margins of trade, and productivity). The five regions are the United States, Japan, Western Europe, Eastern Europe, and Asia.[37]

6.2.1 Data

The model is fitted to annual data for the period 1994–2003, because 1993 is the first year for which data at a high level of disaggregation became available for a large sample of countries. The observable variables of the model are the annual growth in imported varieties, data on output growth, and the fraction of workers employed in R&D. There are 135 observations corresponding to nine years, five regions, and three observable variables.[38]

Bilateral trade data are obtained from the UN COMTRADE database. I follow the HS-1996 classification, which lists goods at the 6-digit level of disaggregation, and restrict the analysis to intermediate products (see Appendix C). Output is measured as GDP per capita PPP adjusted to constant 2005 prices (the data are from the World Bank's World Development Indicators). This measure is adjusted to account for the extensive margin of trade, as explained in Appendix D. Finally, the research intensity of a country is measured by the fraction of workers that are allocated to research (data are from the World Bank's World Development Indicators.)

[36]The code is available upon request.

[37]See Appendix B for the countries grouped within each region.

[38]Dynamic stochastic general equilibrium (DSGE) models that are estimated with Bayesian techniques usually have a long time series for one or two countries. In my case, there is a cross-section dimension in that I have a short time-series sample for five regions.

6.2.2 Shocks

In order to obtain invertibility in the likelihood function, the maximum likelihood approach requires as many shocks as there are observable variables. Given three series of observable variables, I introduce three series of shocks, one for each region: a neutral technology shock a_i in final production, an i.i.d. shock a_{it}^{α} to innovation productivity, and a measurement error in the growth rates of imported varieties.

The structural shocks and measurement errors incorporated in the estimation are:

$$a_{it} = \rho_i a_{i,t-1} + u_{it}$$

with $u_{it} \sim N(0, \sigma_{u,i}^2)$;

$$\xi_{it} \sim N(0, \sigma_i^2)$$

and

$$g_{it}^{obs} = g_{it} e^{me_{it}}$$

with $me_{it} \sim N(0, \sigma_{me,i}^2)$, where me denotes the measurement error and $i = 1, \ldots, 5$.

6.2.3 Parameters

A set of parameters is treated as fixed in the estimation (these are also known as strict priors or calibrated parameters). These parameters cannot be identified from the data; they are obtained from other studies (or from steady-state relations) and are reported in Table 2.

The "iceberg" transport cost, d_n^i, varies across pairs of countries and is proportional to distance. The value is chosen to match the intensive margin of trade.

As in Greenwood, Hercowitz, and Krusell (1997), $\bar{g}$ is chosen so that disembodied growth in steady state represents 40% of the growth of income per capita in equilibrium, which is 2% (this is the growth rate of the United States and rich OECD countries, whose economies are close to the steady state). This implies a value for $\bar{g}$ of 0.8%. Although their analysis is for the United States, we can assume the same value for all the regions in steady state because technology diffusion guarantees that embodied productivity growth in steady state is the same across countries.

The productivity of the innovation process, α_i^R, is set to satisfy equation (19). It is obtained by iteratively estimating the model using the steady-state variables, finding new values for

α_i^R until we obtain an embodied productivity growth of 1.2%. The results show that Asia and Eastern Europe have the lowest productivity of innovation, while the United States and Japan are the most productive.

The parameters to be estimated are the elasticity of substitution across intermediate goods, σ; the elasticity of adoption, γ_a; the extent of diminishing returns in the innovation process, γ_r; the cost of adoption, α_i^A; and the standard deviations, σ_i, of the neutral technology shock and productivity of innovation shocks. The prior mean and standard deviation are included in Table 3 for the structural parameters and in Table 4 for the shock processes.

I assume a Beta distribution for the elasticity of substitution across intermediate goods, with mean 3 and standard deviation 0.05. The prior for α_i^A, the cost of adoption in each region, is distributed Gamma with mean 2 and standard deviation 0.15. The mean is set to match the hazard rates in Table 1, which determine the rate of adoption. The prior for γ_r, the diminishing returns in the innovation process, is set to a Beta distribution with mean 0.1 and standard deviation 0.15.[39] The elasticity of adoption with respect to effort, γ_a, is assumed to follow a Beta distribution with mean 0.4 and standard deviation 0.05.[40]. Finally, I assume an Inverse Gamma distribution for the standard deviation of the shocks, which guarantees a positive variance.

6.3 Estimation results

Tables 3 and 4 report the results from the estimation. The tables contain the prior and posterior mean of the estimated parameters as well as 95% confidence intervals.

The posterior mean for the elasticity of substitution across intermediate goods is 3.5. Broda, Greenfield, and Weinstein (2008) estimate a median elasticity of substitution equal to 3.4 for a sample of 73 countries. The value that I obtain lies between the one obtained in microeconomic models and the one obtained in macroeconomic models.

The posterior mean for the adoption costs, reported in Table 4, lies between 1.7 and 2. It does not follow a particular pattern across regions. These figures can be used to compute

[39] Eaton and Kortum (1999) find a value of about 0.2 for this parameter; Griliches (1990), using the number of new patents as a proxy for technological change, obtains estimates ranging between 0.5 and 1.

[40] This parameter has been calibrated by Comin and Gertler (2006) and Comin, Gertler, and Santacreu (2009), who find that a reasonable value in a closed-economy model is 0.8. Because there are no good measures of adoption expenditures or adoption rates, they use as a partial measure the development costs incurred by manufacturing firms to make the goods usable (this is a subset of R&D expenditures). Then they regress the rate of decline of the relative price of capital with respect to the partial measure of adoption costs. The idea is that the price of capital moves countercyclically with the number of new adopted technologies and therefore is a measure of embodied adoption. The regression yields a constant of 0.8.

ε^i_{nt}, the probability of adoption predicted by the model. The average probability of adoption for the period 1994–2003 is presented in the last column of Table 5. The results imply that the average time it takes for a country to use an intermediate good developed elsewhere—the inverse of the probability of adoption—is between two and ten years.

The posterior mean for the elasticity of innovation γ_r is 0.025, which is close to the results in Eaton and Kortum (1999) but much lower than those in Griliches (1990). Finally, the elasticity of adoption is estimated to be 0.45. This parameter is reported for a closed economy by Comin and Gertler (2006), who estimate a value of 0.8. The lower value for α_A implies that the elasticity of adoption is lower in an open economy than in a closed economy, suggesting that countries need to invest more resources in adoption to import a foreign than a domestic good.

6.4 How well does the model fit the data?

This section analyzes the fit of the model by comparing several variables for which we can find a counterpart in the data: the rate of adoption as well as several moments relating growth in imports, R&D intensity, and GDP per capita growth.

The rate of adoption was computed in Section 2. The estimated value is computed by simulating the model while using the value of the parameters and the series of shocks from the estimation. The results are reported in Table 5.

Overall, the model captures the average adoption probability for the five regions. In the data and in the model, the lag averages between three and ten years, and the United States and Japan tend to have the highest rates. Other studies that have quantified the speed of adoption are Eaton and Kortum (1999) and Comin and Hobijn (2004). The first study uses international patent data to measure international diffusion, whereas the second uses direct measures of technology for many countries and a long period of time. To my knowledge, my paper is the first to estimate hazard rates of adoption using trade data.

I now compare several moments in the data and the model. Using the estimated parameters and standard deviations of the shocks, I run 1,000 draws from the shocks in the model and then compute the correlations between growth in imports and real GDP per capita growth, between R&D intensity and real GDP per capita growth, and between R&D intensity and growth in imports. The results are reported in Table 6. As in the data, R&D and trade are negatively correlated across countries; the same is true for R&D and productivity growth. Countries that invest less in R&D are also importing and growing at higher rates, since they benefit from the lower costs of adoption (compared to innovation) and catching up. The

model also captures the positive correlation between growth in imports and GDP per capita, since countries that have expanded imports are also growing faster. The model not only captures the signs of the relations but also their magnitude. In the data, the correlation between growth and trade is 0.6, while the model predicts a correlation of 0.7. In the case of R&D and trade and the case of R&D and growth, the correlations in the data are respectively -0.32 and -0.28, while the model predicts correlations of -0.21 and -0.31.

7 Decomposition of productivity growth

7.1 Embodied versus disembodied productivity

In the model, economic growth is decomposed into (i) embodied growth, captured by an expansion in the number of intermediate goods, and (ii) disembodied growth, captured by an exogenous TFP shock.[41] Taking the estimated series of the TFP shock together with data on output growth from the empirical analysis, I compute the contribution of both sources of growth. Table 7 reports the results.[42]

Embodied growth has contributed to about 80% of the productivity growth in Asia and Eastern Europe, and to roughly two thirds of total growth in the the United States, Japan, and Western Europe. These numbers suggest that rich countries are closer to the steady-state values found by Greenwood, Hercowitz, and Krusell (1997). In developing countries, however, growth is mainly driven by transitional dynamics.

7.2 Contribution of domestic and foreign sources of innovation to growth

Table 8 reports the contribution of domestic and foreign sources of innovation to embodied productivity growth. In the table, the rows are for the destination country (importer) and the columns are for the source country (exporter). Each entry in the matrix contains the percentage of the embodied productivity growth in each row that is explained by technologies developed in each column, averaged over the period 1994–2003. The boldface numbers in the diagonal measure the contribution of domestic sources of innovation.

[41] Think of this TFP shock as capturing all sources of growth not explained by love for variety. In that sense, one could view this section as an empirical test of the love-for-variety models.

[42] The numbers represent averages over the period 1994-2003. Note that for the case in steady state, I had calibrated disembodied technology to represent 60% of productivity growth in the country, as in Greenwood, Hercowitz, and Krusell (1997).

The results show that more than 80% of embodied growth in Asia (which, by Section 7.1, corresponds to 64% of total growth) can be explained by foreign innovations embodied in imports—especially from the United States, Japan, and Western Europe. These regions have by far the highest percentage of growth accounted for by domestic innovation, with about 30% of embodied productivity coming from each country's own innovative effort. The results are consistent with the empirical evidence: Asia does relatively little research but has experienced a rapid increase in imported varieties—especially from the United States and Japan, which are the most innovative regions.

The results off the diagonal in Table 8 can be further decomposed to obtain the contribution of each exporter; Table 9 reports the results. About two thirds of the contribution of foreign sources of innovation in Europe and Asia proceed from Japan and the United States together. Asia and Eastern Europe's innovations contribute only some 10% to embodied productivity growth in the other regions.

The results reported in Tables 8 and 9 incorporate data on research intensity as a measure of innovation, not data on the number of exported products. In Table 10 I compute the same decomposition, but now using data on exported varieties at the bilateral level. Table 10 reports the percentage of each importer's total imports that is explained by each exporter. The results are qualitatively similar to those derived when only innovation data are used. In Asia, 4% of total imports in varieties comes from less innovative countries in Europe. The United States and Japan together account more than 50% of imported varieties in each region; Asia and less innovative EU contribute the least. Comparing the results in Tables 9 and 10 suggests it is plaussible to assume that R&D is embodied in exports, since the main exporters are the main innovators and since both foreign innovation and exports from these countries have the greatest impact on the embodied growth of developing countries.

8 Speed of convergence: Where will the world be in the long run?

This section shows how long it will take for each region to reach U.S. levels of income per capita. To do this, I use the estimated value of the structural parameters and the standard deviation of the shocks and simulate the model for 1,000 periods.

Table 11 summarizes the results. Asia's income per capita in 1995 was 25% of the U.S. income per capita. Japan is at the other extreme, with 80% of the income. Europe lies in

the middle: Eastern Europe is closer to Asia, but Western Europe is closer to Japan.

The first and third data columns in Table 11 show how close each region will be to the technology frontier once they are halfway to the new steady state. Asia will improve its position by 72%, and this will take 80 years. Japan, which is closer to the United States, takes 35 years but improves by only 5%. Countries that lag behind (Asia and Eastern Europe) take longer to get closer, but their percentage improvement is greater. As convergence predicts, the gap is rediced more slowly when a country approaches the steady state.

Note that the technology frontier is always moving forward because of every country's investment in innovation. In steady state, countries close the gap but there is no (complete) catching up in the levels of income per capita. This can be explained by differences in policies and institutions, which are reflected in country-specific parameters of innovation and adoption.[43]

9 Counterfactuals

I perform two experiments to show how changes to the parameters of innovation and adoption can explain the connections between trade and growth. The experiments have implications for world growth rates, research intensity, income per capita, and the extensive and intensive margins of trade.

Starting from the steady state of the model, I introduce two policy changes, as follows.

- A 50% permanent decrease in the barriers to technology transfer in Asia; that is, an increase in $\alpha^A(Asia)$ in equation (7).
- A 50% permanent increase in the productivity of innovation in Asia; that is, an increase in $\alpha^R(Asia)$ in equation (6).

I explore the transition path to the new equilibrium and then perform comparative statics between the two steady states in Asia (the region incorporating the policy change) and the United States (the technology frontier). The two experiments lead to higher trade and also to faster growth.

[43]This was observed by Klenow and Rodriguez-Clare (2005).

9.1 Counterfactual: 50% reduction in Asian adoption costs

9.1.1 Steady state

Table 12 presents the comparative statics for the key variables. Observe that a 50% reduction in the cost of adoption in Asia increases world growth rates by 0.7%.

Research intensity is higher in the new steady state. Asia benefits from the spillover effect in equation (6) and experiences a 2.3% increase in the intensity of innovation. This results in a higher diversification of exports in the region. The United States benefits from a demand effect, as the ability to adopt goods increases the demand for imports—especially from Japan and the United States, who are the main exporters. The positive demand effect increases the present discounted value of future profits from selling a good abroad, which increases the market price for an innovation and, ultimately, the exporter's research intensity.

The extensive margin in Asia increases for two reasons. First, a higher probability of adoption raises imports.[44] Second, higher imports increase the productivity of innovation (via the spillover effect), which increases domestic innovation. This is in line with what Goldberg, Khandelwal, Pavcnik, and Topalova (2009) found when analyzing trade liberalization in India. Lower trade costs increase imports of inputs and hence the scope of products.

In summary, Asia closes the distance with respect to the United States, both in the number of varieties that it produces domestically and in the proportion of goods that it adopts from the technology frontier. This catching-up effect translates into a 70% increase in the relative wage of Asia with respect to the United States. In the new steady state, growth rates are constant and common across countries. However, there is still a gap in levels of income per capita; these gaps are due to differences in the country-specific parameters. There is convergence in growth rates but not in levels of income per capita.

9.1.2 Transitional dynamics

Figure 5 depicts the transition path to the new steady state. In the first (upper left) panel it is clear that the research intensity in Asia (solid line) decreases in the response of the policy change. There is an initial reallocation of resources away from research and in to adoption. As a result, Asia begins to import more varieties and so the extensive margin of trade increases. A number of periods later, the spillover effect kicks in, increasing the

[44]The probability of adoption in Asia increases for two reasons: directly, from an increase in $\alpha^A(Asia)$ and indirectly, from an increase in (a) the investment in adoption, H^i_{nt}, and (b) the proportion of new goods that Asia imports from the United States, $\frac{A^i_{nt}}{Z_{nt}}$.

productivity of innovation in the region. Hence research intensity increases and reaches a higher level in the new steady state.

A higher value of $\alpha^A(Asia)$ implie an increase in the value of adopting new technologies and thus of investing in adoption. This occurs at the intensive and extensive margins of trade (solid and dashed line in the first panel): Asia imports more goods and more of the same goods. At the same time, this positive demand effect increases investment in innovation in the United States (dashed line in the first panel). Asia eventually becomes closer to the United States, through an increase in both imported and domestic varieties. Yet even though the gap gets smaller, wages remain higher in the United States (lower right panel of Figure 5).

This experiment generates both higher trade and faster growth. Note that the results are consistent with the findings of Goldberg, Khandelwal, Pavcnik, and Topalova (2009). There are static gains from trade because countries benefit from access to new intermediate inputs; there are also dynamic gains from trade because adoption enables countries to innovate more.[45]

This scenario seems to match the data. During the transition, rich countries allocate more resources into R&D while less advanced countries adopt foreign innovations, which translates into more growth. However, Asia still trails the United States in terms of income per capita owing to the initial differences caused by country-specific parameters. Adoption alone is not sufficient to completely close the gap.

9.2 Counterfactual: 50% increase in Asian productivity of innovation

9.2.1 Steady state

Table 13 presents the results of this exercise. Observe that a 50% increase in the productivity of innovation in Asia increases world growth rates by 3%.

Research intensity in the new steady state is higher in Asia, but lower in the United States. Higher productivity of innovation reduces the cost of doing research in the region; then after several periods, the spillover effect kicks in, and the cost of innovation decreases even more. The result is an 80% increase in research intensity. Note that higher productivity of innovation in Asia is due both to higher α^R and to the spillover effect. Both factors have a

[45] Arkolakis, Klenow, Demidova, and Rodriguez-Clare (2008) show that, depending on the curvature of the CES function, the level of innovation following a trade liberalization could be higher, lower, or unchanged.

negative impact on research intensity in the trading partners. However, this negative effect is partially compensated by a higher demand for innovations—especially at the intensive margin—once Asia gets closer to the technology frontier.

Asia closes the gap with respect to the technology frontier, both in the number of varieties that it produces domestically and in the proportion of goods that it adopts. Relative wages increase by 40%. As in the previous experiment, Asia does not entirely catch up with the United States. In fact, the increase in relative wages is lower than before. This suggests that, in early stages of development, adoption policies are more effective promoting growth than innovation policies.

9.2.2 Transitional dynamics

Figure 6 presents the transition path to the new steady state. A higher $\alpha^R(Asia)$ decreases the cost of innovation, so Asia starts reallocating resources away from adoption and in to research. Thus, the demand for imports decreases initially, which has a negative effect on research intensity in the United States because of a decrease in the market price of an innovation.

Asia starts producing new goods, and the domestic extensive margin increases. More innovation translates into more growth and more demand at the intensive margin. At this point, the demand for products from the United States increases (upper left panel in Figure 6) and research intensity speeds up. However, this increase is not enough to compensate for the initial negative demand effect.

In the transition, Asia closes the gap with respect to the leader through an increase in imported varieties and an increase in innovations (upper left panel). Wages relative to those in the United States decrease, but less so than in the previous experiment. In early stages of development, adoption policies are more effective at promoting growth than innovation policies. However, once the country has built a certain level of technology, promoting innovation is necessary to continue growing.

10 Conclusions

The effects of trade on growth have been studied extensively in economics. However, there are still significant gaps in the literature. Neither the mechanisms nor the magnitude by which countries benefit from each other's technologies through trade are fully understood.

In this paper I have proposed innovation (through the creation of new varieties) and

diffusion (through adoption of foreign innovations) as possible mechanisms. In countries at an early stage of development, the relative cost of adoption to innovation is small. By adopting foreign innovations they benefit from a catching-up effect and grow faster than average. As these countries move along the transition path, they need to invest resources in innovation in order to keep growing and to keep expanding the technology frontier. In this explanation, technological progress derives from a love-for-variety effect that captures embodied productivity growth. Other channels of growth are captured by an exogenous change that represents disembodied productivity.

The paper is one step forward in analyzing the connections between trade in varieties and growth. It does not suffer from the endogeneity problem of regression analysis, and the model is tractable enough to analyze the mechanisms outside of steady state. These features are important for capturing differences in growth rates across countries. The model also provides the microeconomic mechanisms to explain how trade in varieties generates both static (through an increase in previously unavailable inputs) and dynamic (through an expansion in the number of goods produced domestically) gains from trade.

In applying the model to data on innovation, productivity, and trade, I have shown that more than two thirds of growth in the last decade has been embodied growth. The proportion is even higher for Asia and Eastern Europe, which suggests that growth in these countries has been dominated by the transitional dynamics. In contrast, Japan and the United States are closer to the steady state. The empirical analysis also shows that regions at early stages of development benefit from foreign innovations, although domestic innovationis more important in the United States, Japan, and Western Europe. For countries that lag behind, the most efficient way to approach the technology frontier is to adopt foreign technologies via imports. As such countries become more developed, they must innovate in order to keep growing.

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11 Tables and graphs

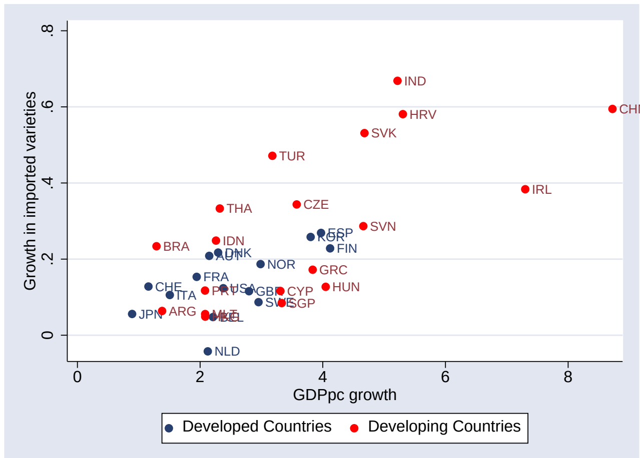

Figure 1: GDP per capita growth and growth in imported varieties (1994–2003)

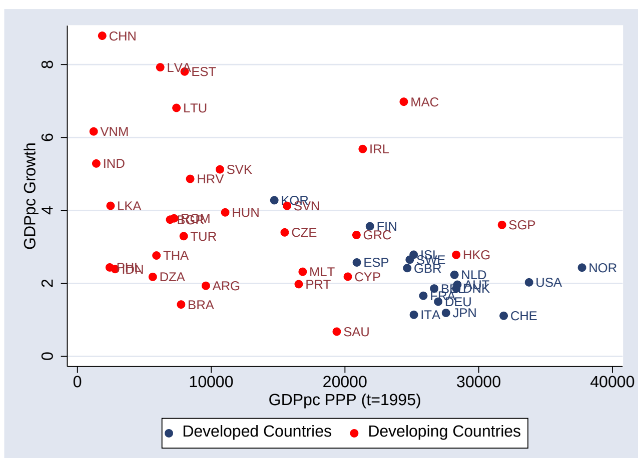

Figure 2: GDP per capita growth and initial level of GDP per capita (1994–2003)

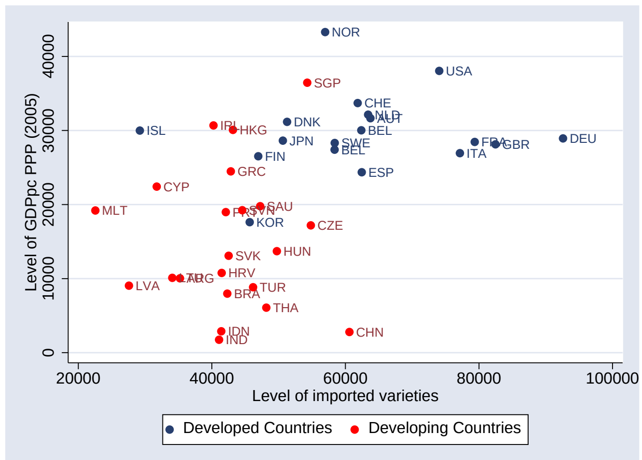

Figure 3: Level of GDP per capita and number of imported varieties (1994–2003)

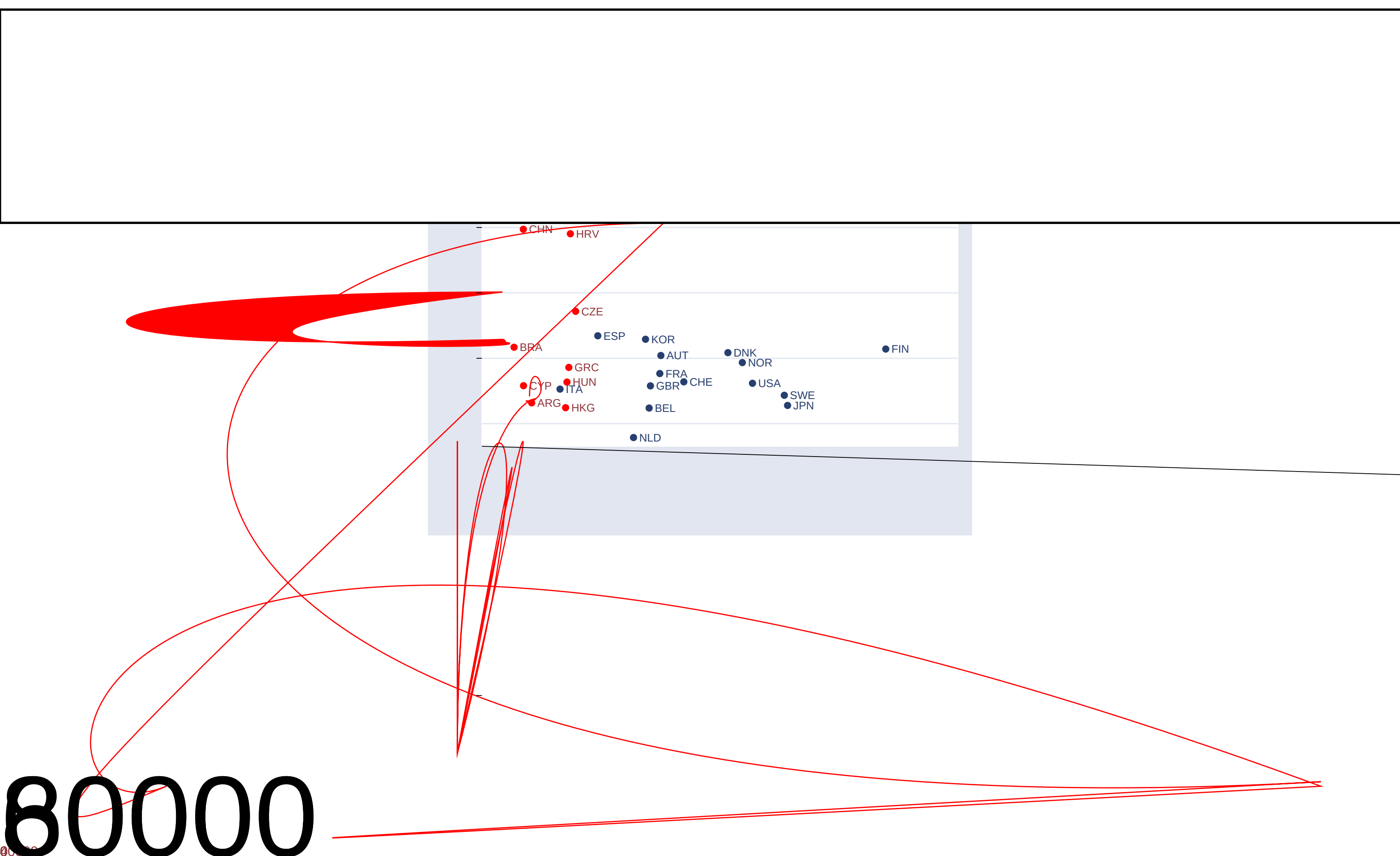

Table 1: Hazard rates of adoption

Exporter	Importer	Hazard rate
WE	Asia	0.31
EE	Asia	0.19
Japan	Asia	0.35
U.S.	Asia	0.34
Asia	WE	0.28
EE	WE	0.33
Japan	WE	0.29
U.S.	WE	0.28
Asia	EE	0.24
WE	EE	0.33
Japan	EE	0.31
U.S.	EE	0.34
Asia	Japan	0.35
WE	Japan	0.28
EE	Japan	0.20
U.S.	Japan	0.25
Asia	U.S.	0.35
WE	U.S.	0.29
EE	U.S.	0.32
Japan	U.S.	0.28

Key: WE (Western Europe); EE (Eastern Europe); Japan (includes Korea)

Table 2: Calibrated parameters

Parameter	Value	Description
β	0.97	Discount factor
$d(\text{Asia}, \text{EE})$	1.30	Iceberg transport costs
$d(\text{Asia}, \text{WE})$	1.30	Iceberg transport costs
$d(\text{Asia}, \text{Japan})$	1.10	Iceberg transport costs
$d(\text{Asia}, \text{U.S.})$	1.30	Iceberg transport costs
$d(\text{EE}, \text{WE})$	1.05	Iceberg transport costs
$d(\text{EE}, \text{Japan})$	1.40	Iceberg transport costs
$d(\text{EE}, \text{U.S.})$	1.30	Iceberg transport costs
$d(\text{WE}, \text{Japan})$	1.40	Iceberg transport costs
$d(\text{WE}, \text{U.S.})$	1.30	Iceberg transport costs
$d(\text{Japan}, \text{U.S.})$	1.30	Iceberg transport costs
$\bar{g}$	0.02	Disembodied growth in steady state
$\alpha^R(\text{Asia})$	0.0082	Innovation productivity
$\alpha^R(\text{EE})$	0.0186	Innovation productivity
$\alpha^R(\text{WE})$	0.0237	Innovation productivity
$\alpha^R(\text{Japan})$	0.0288	Innovation productivity
$\alpha^R(\text{U.S.})$	0.0268	Innovation productivity

Table 3: Prior and posterior for the structural parameters

Parameter	Prior	Mean	5%	95%
σ	Beta(3, 0.05)	3.55	2.70	4.80
α^A(Asia)	Gamma(2, 0.15)	2.11	1.86	2.33
α^A(EE)	Gamma(2, 0.15)	1.92	1.75	2.10
α^A(WE)	Gamma(2, 0.15)	1.90	1.70	2.13
α^A(Japan)	Gamma(2, 0.15)	2.04	1.83	2.22
α^A(U.S.)	Gamma(2, 0.15)	1.95	1.73	2.22
γ_a	Normal(0.4, 0.05)	0.45	0.33	0.53
γ_r	Beta(0.15, 0.10)	0.025	0.019	0.03

Note: The values in parentheses correspond to the mean and the standard deviation.

Table 4: Prior and posterior for the shock processes

Parameter	Prior	Mean	5%	95%
σ(Asia)	IGamma(0.25,∞)	0.19	0.12	0.28
σ(EE)	IGamma(0.25,∞)	0.20	0.14	0.27
σ(WE)	IGamma(0.25,∞)	0.04	0.04	0.05
σ(Japan)	IGamma(0.25,∞)	0.04	0.04	0.04
σ(U.S.)	IGamma(0.25,∞)	0.09	0.06	0.10
σ^r(Asia)	IGamma(0.25,∞)	0.83	0.66	0.96
σ^r(EE)	IGamma(0.25,∞)	0.58	0.55	0.62
σ^r(WE)	IGamma(0.25,∞)	0.29	0.28	0.29
σ^r(Japan)	IGamma(0.25,∞)	0.52	0.44	0.61
σ^r(U.S.)	IGamma(0.25,∞)	0.31	0.30	0.32
me(Asia)	IGamma(0.025,∞)	0.66	0.52	0.81
me(EE)	IGamma(0.025,∞)	0.54	0.40	0.80
me(WE)	IGamma(0.025,∞)	0.81	0.78	0.84
me(Japan)	IGamma(0.025,∞)	0.79	0.43	1.10
me(U.S.)	IGamma(0.025,∞)	0.62	0.59	0.65

Notes: IGamma = Inverse Gamma. The values in parentheses correspond to the mean and the standard deviation.

Table 5: Hazard rates of adoption (data and model)

Exporter	Importer	Hazard rate(data)	Hazard rate (model)
WE	Asia	0.31	0.22
EE	Asia	0.19	0.24
Japan	Asia	0.35	0.21
U.S.	Asia	0.34	0.19
Asia	WE	0.28	0.27
EE	WE	0.33	0.26
Japan	WE	0.29	0.23
U.S.	WE	0.28	0.20
Asia	EE	0.24	0.20
EU	EE	0.33	0.18
Japan	EE	0.31	0.26
U.S.	EE	0.34	0.24
Asia	Japan	0.35	0.26
WE	Japan	0.28	0.23
EE	Japan	0.20	0.25
U.S.	Japan	0.25	0.21
Asia	U.S.	0.35	0.29
WE	U.S.	0.29	0.26
EE	U.S.	0.32	0.28
Japan	U.S.	0.28	0.25

Note: Mean square error = 0.01.

Table 6: Comparison of unconditional moments: Model versus data

Correlation	Model	Data
(R&D, Trade)	-0.21	-0.32
(Growth, Trade)	0.70	0.60
(Growth, R&D)	-0.31	-0.28

Table 7: Embodied versus disembodied productivity growth in the transition (percentage)

Region	Embodied	Disembodied
Asia	80	20
EE	72	18
WE	67	33
Japan	63	37
U.S.	68	32

Table 8: Sources of growth predicted by the model: Domestic and foreign innovation

To—From	Asia	EE	WE	Japan	U.S.
Asia	**11.2**	14.6	21.0	28.4	24.9
EE	5.6	**21.4**	24.9	25.0	23.0
WE	5.9	17.6	**27.5**	25.5	23.5
Japan	6.7	15.0	21.1	**32.7**	24.5
U.S.	6.4	15.0	21.2	26.6	**30.8**

Table 9: Foreign sources of growth: Bilateral contribution predicted by the model

To—From	Asia	EE	WE	Japan	U.S.
Asia		16.4	23.6	32.0	28.0
EE	7.1		31.7	31.9	29.3
WE	8.2	24.3		35.2	32.4
Japan	10.0	22.2	31.4		36.4
U.S.	9.2	21.7	30.7	38.4	

Table 10: Foreign sources of growth: Bilateral contribution in the data

To—From	Asia	EE	WE	Japan	U.S.
Asia		4.1	19.2	36.3	40.4
EE	9.3		37.1	15.9	37.6
WE	14.3	15.5		22.9	47.4
Japan	20.0	5.4	22.6		51.9
U.S.	20.9	10.9	31.1	37.1	

Table 11: Speed of convergence

Region	Years to convergence	Relative income pc (1995)	Improvement
Asia	80	25%	72%
Eastern Europe	60	26%	60%
Western Europe	50	69%	50%
Japan	35	80%	35%
U.S.	Baseline	Baseline	Baseline

Table 12: Reduction in adoption barriers in Asia: steady state comparison

Variable	% change
$\Delta r(\text{Asia})$	2.3%
$\Delta r(\text{U.S.})$	2.6%
Δg^*	0.7%
$\Delta \frac{\omega(\text{Asia})}{\omega(\text{U.S.})}$	70%
$\Delta \frac{Z(\text{Asia})}{Z(\text{U.S.})}$	11%
$\Delta \frac{A_{\text{U.S.}}^{\text{Asia}}}{Z_{\text{U.S.}}}$	10%

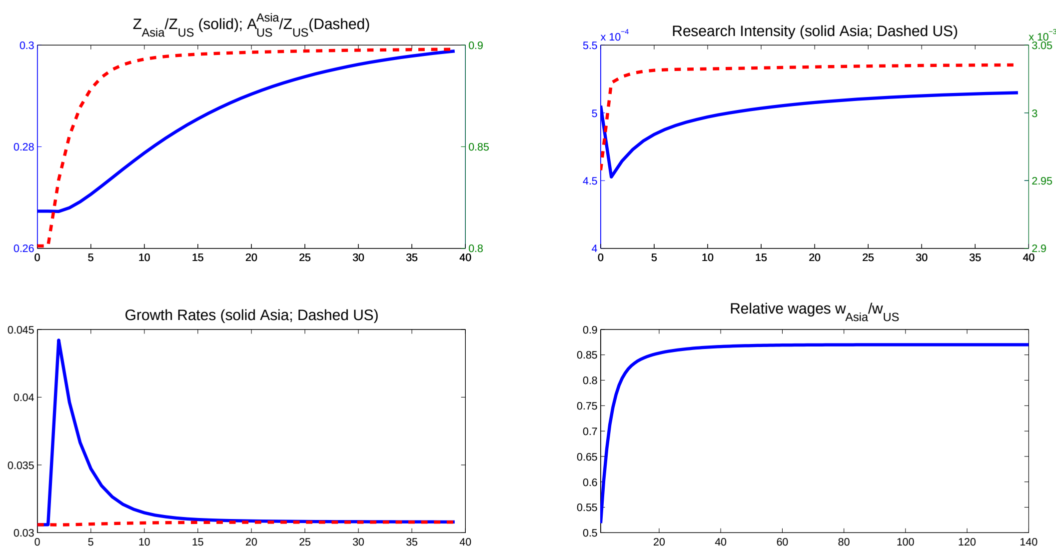

Figure 5: Permanent reduction in barriers to adoption in Asia

Table 13: Increase in innovation productivity in Asia: steady state comparison

Variable	% change
$\Delta r(Asia)$	88%
$\Delta r(U.S.)$	-3%
g^*	3.2%
$\frac{\omega(\text{Asia})}{\omega(\text{U.S.})}$	40%
$\Delta\frac{Z(\text{Asia})}{Z(\text{U.S.})}$	37%
$\Delta\frac{A^{\text{Asia}}_{\text{U.S.}}}{Z_{\text{U.S.}}}$	2%

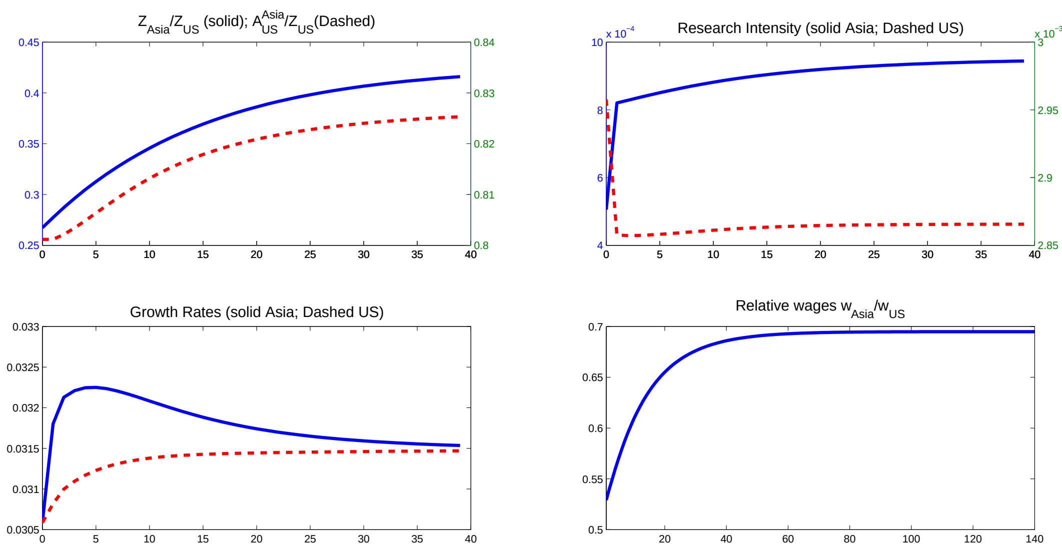

Figure 6: Permanent increase in innovation productivity in Asia

A Data

Country	GDPpcgrowth	Varietygrowth	Researchers	GDPpc(1995)
Austria	1.94	0.03	2.72	28,401.87
Belgium	1.93	0.16	2.89	26,668.76
Bulgaria	2.17	0.83	0.56	6,924.32
China	8.13	0.55	0.42	1,853.45
Cyprus	2.39	0.71	4.05	20,212.69
Denmark	2.03	0.30	2.21	28,323.68
Estonia	6.16	0.85	6.65	7,911.48
Finland	3.38	0.40	2.95	21,865.56
France	1.75	0.03	3.10	25,856.33
Germany	1.38	0.04	1.26	26,970.08
Greece	2.88	0.24	1.32	20,861.02
Hong Kong	1.79	0.59	1.32	27,175.87
Hungary	3.87	0.26	0.10	11,048.27
India	4.20	1.96	0.21	1,403.71
Indonesia	1.78	1.93	2.28	2,815.82
Ireland	6.54	0.34	2.28	21,328.97
Italy	1.52	0.01	1.19	25,151.35
Japan	0.72	0.13	5.17	27,551.29
Korea	4.37	0.28	2.70	14,716.83
Latvia	6.04	1.22	1.33	6,190.58
Lithuania	4.28	1.20	2.17	7,402.13
Malaysia	2.81	1.11	0.28	9,296.93
Malta	2.69	1.46	0.70	16,839.78
Netherlands	2.21	0.47	2.53	28,186.20
Philippines	1.78	1.19	0.05	2,415.27
Poland	4.53	0.41	1.48	8,836.75
Portugal	2.26	0.20	1.65	16,543.51
Romania	2.45	0.69	1.06	7,223.41
Singapore	3.08	0.43	3.89	30,922.08
Slovakia	3.99	0.54	1.86	10,651.25
Slovenia	3.74	0.15	2.32	15,410.37

Country	GDPpcgrowth	Varietygrowth	Researchers	GDPpc (1995)
Spain	2.75	0.08	1.78	20,887.66
Sweden	2.56	0.15	4.85	24,843.19
Thailand	2.39	0.50	0.22	5,907.27
UK	2.72	0.05	2.99	24,555.60
U.S.	2.04	0.07	4.50	33,759.57
Vietnam	5.78	1.79	0.16	1,214.14
Asia	3.53	1.12	0.98	9,222.73
EE	3.64	0.57	1.91	13,963.97
WE	2.21	0.18	2.83	26,185.70
Japan	2.55	0.20	3.94	21,134.06
U.S.	2.04	0.07	4.50	33,759.57

B Country list

Bloc	Country code	Country name
Africa	SAU	Saudi Arabia
Asia	CHN	China
Asia	HKG	China, Hong Kong SAR
Asia	IDN	Indonesia
Asia	IND	India
Asia	SGP	Singapore
Asia	THA	Thailand
Eastern Europe	CYP	Cyprus
Eastern Europe	CZE	Czech Republic
Eastern Europe	GRC	Greece
Eastern Europe	HRV	Croatia
Eastern Europe	HUN	Hungary
Eastern Europe	IRL	Ireland
Eastern Europe	LTU	Lithuania
Eastern Europe	LVA	Latvia
Eastern Europe	MLT	Malta
Eastern Europe	POL	Poland
Eastern Europe	PRT	Portugal
Eastern Europe	SVK	Slovakia
Eastern Europe	SVN	Slovenia
Eastern Europe	TUR	Turkey
Japan	JPN	Japan
Japan	KOR	Korea
LatinAmerica	ARG	Argentina
LatinAmerica	BRA	Brazil
United States	U.S.	United States
Western Europe	AUT	Austria
Western Europe	BEL	Belgium
Western Europe	CHE	Switzerland
Western Europe	DEU	Germany
Western Europe	DNK	Denmark

Bloc	Country code	Country name
Western Europe	ESP	Spain
Western Europe	FIN	Finland
Western Europe	FRA	France
Western Europe	GBR	United Kingdom
Western Europe	ISL	Iceland
Western Europe	ITA	Italy
Western Europe	NLD	Netherlands
Western Europe	NOR	Norway
Western Europe	SWE	Sweden

C Product classification

The codes are stipulated by the UN's Broad Economic Categories (BEC) classification, which groups external trade data in terms of the three basic classes of goods in the System of National Accounts (SNA).

1. Capital goods
Sum of categories:
41* Capital goods (except transport equipment)
521* Transport equipment, industrial
2. Intermediate goods
Sum of categories:
111* Food and beverages, primary, mainly for industry
121* Food and beverages, processed, mainly for industry
21* Industrial supplies not elsewhere specified, primary
22* Industrial supplies not elsewhere specified, processed
31* Fuels and lubricants, primary
322* Fuels and lubricants, processed (other than motor spirits)
42* Parts and accessories of capital goods (except transport equipment)
53* Parts and accessories of transport equipment
3. Consumption goods
Sum of categories:
112* Food and beverages, primary, mainly for household consumption
122* Food and beverages, processed, mainly for household consumption
522* Transport equipment, non-industrial
61* Consumer goods not elsewhere specified, durable
62* Consumer goods not elsewhere specified, semidurable
63* Consumer goods not elsewhere specified, nondurable

D Measuring real GDP

The measure of real GDP that is used in the empirical analysis was computed while accounting for the effect of differences in the terms of trade across countries and the extensive margin of trade in the price of imported intermediate goods.

As recently argued by Feenstra, Heston, Timmer, and Deng (2009), the World Development Indicators and Penn World Table (PWT) measure of real GDP represents the ability of a representative agent in the country's economy to purchase goods and services. But this interpretation of real GDP differs from the one used in growth analysis, where GDP per

capita is measure of productivity. To compute real GDP from the output side, Feenstra, Heston, Timmer, and Deng (2009) correct the PWT measure for differences in the terms of trade across countries. This difference reflects the trading opportunities that countries have (as measured by their ratio of export prices to import prices), and it is shown empirically, that the differences can be substantial—especially for small open economies.

To make the measure of real GDP growth from the output side comparable with the real GDP used in my model, an adjustment must be made for the extensive margin of imports.Toward this end, I use the procedure followed in Broda, Greenfield, and Weinstein (2008). The difference between the adjusted and unadjusted calculations gives a measure of the impact of product variety in trade on productivity, or of the gains from trade due to product variety.

E Hazard rates of adoption

I use the tools of survival analysis (or duration analysis) with censored data. I estimate a nonparametric survival function (using the Kaplan–Meier estimator with right-censored data). Ideally, we would need to know the time at which each good is invented by the exporter and the time at which it is first imported by each destination. There are several limitations in the data. First, I do not observe the time of invention. Instead, I assume that this is given by the first time a source starts exporting a good to any country.

Second, there are left and right censoring in the data. There is left censoring because we do not know if products exported in 1994 were invented in that year or earlier. There is right censoring because some importers had not adopted, before 2003, all the goods that had been exported. It is easy to fix the problem of right censoring, but dealing with left-censored data is more problematic (though it is straightforward to handle if we assume that the hazard rate does not vary with survival time). The standard way to deal with left censoring is to drop the spells that started before the window of observation.